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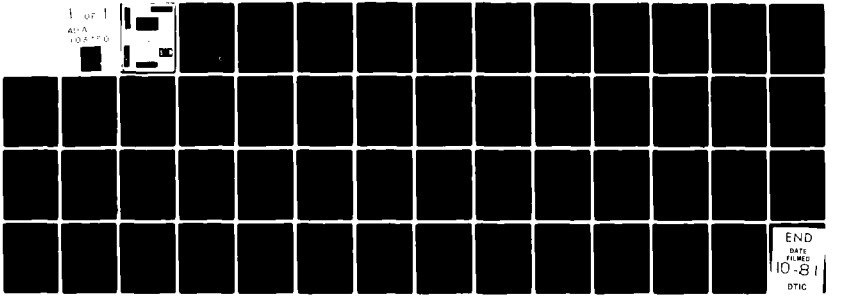

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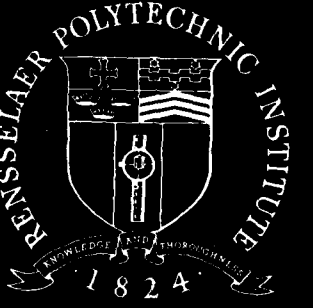

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AN ATTRIBUTED LL(1) COMPILATION OF PASCAL INTO THE LAMBDA-CALCULUS

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INTRODUCTION

This report describes a PASCAL compiler which is rather unique in that its target language is the lambda-calculus instead of some machine code. Although the object code that it generates can be executed by means of a lambda-expression-reducer [3] (resembling a pure LISP interpreter), the intended use of the code is in proving programs correct.

The compiler is written in PASCAL itself and contains an attributed LL(1) parser [7] of the complete standard PASCAL language [5]. Its error recovery is quite elaborate and it provides substantially better error diagnostics than several existing standard PASCAL compilers [9]. It produces code for a large subset of standard PASCAL, covering most programs that are interesting from the theoretical program-verification viewpoint. The translated features include: multidimensional arrays, assignment statements in their generality, I/O statements, compound, conditional and repetitive statements, procedures, with recursive calls and global side effects allowed.

This report is divided into two parts: The first part gives a formal definition of the version of lambda-calculus used as the target language, and describes the representation rules to translate PASCAL programs into the lambda-calculus. The second part contains a code-independent description of compilation algorithms including the complete LL(1) push-down automaton. It is assumed that the reader is familiar with the basic ideas of the lambda-calculus [4,10] and the top-down parsing methods [7].

PART 1: THE TARGET LANGUAGE

1.1. Introduction

The target language of the compiler is a slightly modified form of the lambda-calculus [4,10]. The structure of the PASCAL source program will be partially preserved by the translation into this language. Theoretically, an object program could be converted into a single lambda-expression. However, this is undesirable since the resulting code will lack clarity and will be inefficient for later automatic evaluation. Furthermore there is a ("software") machine which will execute this language in a slightly different syntactic setting [3]. This part introduces the essential concepts of the calculus and its modelling capabilities for PASCAL programs. For a detailed discussion of the lambda-calculus model of ALGOL-like programming languages, the reader is referred to [1,2].

1.2. The Lambda-Calculus

Adopting a commonly used terminology [1], the syntax of the lambda-calculus is given by the following BNF-definition:

(1) <indeterminate> ::= <PASCAL-identifier including '$' in the letter set>
(2) <lambda-expression> ::= <indeterminate>
(3) <lambda-expression> ::= <application>
(4) <lambda-expression> ::= <abstraction>
(5) <application> ::= (<lambda-expression> <lambda-expression>)
(6) <abstraction> ::= (%<binding indeterminates>:<lambda-expression>)[+]
(7) <binding indeterminates> ::= <indeterminate>

When using multi-character symbols, it may be necessary to separate the lambda-expressions in production (5) by blank spaces. Blank spaces are allowed also whenever no syntactic unit is split apart. The lambda-expression in production (6) is the scope of the preceding binding indeterminates. An instance of an indeterminate within a given lambda-expression is bound if it occurs in the scope of a same binding indeterminate. However, it is bound by only the same innermost binding indeterminate. Otherwise its occurence is free in this lambda-expression. If e, f1, f2,..., fn are lambda-expressions and x1, x2,..., xn are

---

[+] Note that the percent sign is used to denote the Greek letter lambda, because the printer on which this document is being produced is not equipped with a Greek character font.

pairwise distinct indeterminates[+], then

sub[f1,x1; f2,x2;...; fn,xn; e]

denotes the result of simultaneously substituting fi for all free occurences of xi ($1 \leq i \leq n$) in e.

The lambda-calculus contains the following contraction and expansion rules:

Alpha-conversion (renaming bound variables):
(% x: e) —(alpha)—> (% y: sub[y,x; e]) provided that y has no free occurence in e.

Beta-contraction (substitution):
((% x: e)f) —(beta)—> sub[f,x; e] if no free indeterminates in f occur bound in e.

Eta-contraction (extensionality):
(% x:(e x)) —(eta)—> e if x does not occur free in e.[++]

The converses of beta- and eta-contractions are called beta- and eta-expansions, respectively. A (possibly empty) sequence of contractions and alpha-conversions is called reduction (denoted by "—>"). Conversion ("<—>") also includes expansions. An irreducible lambda-expression cannot be beta- or eta-contracted further. If a lambda-expression e can be converted into an irreducible lambda-expression f, then f is uniquely determined up to alpha-conversions and, futhermore, e —> f. The leftmost (outermost) computation rule is safe in the sense that it always leads to this irreducible lambda-expression ("normal form") provided that this expression exists. Most results may be proved using the Church-Rosser Theorem [4]: If e <—> g, then there is a conversion from e into g in which no expansion preceeds any contraction.

The following lemma suggests a useful extension of the syntax for lambda-expressions:

Lemma:
(...((%x1:(%x2:(...(%xn:e)...)))f1)...fn)—>sub[f1,x1;f2,x2;...; fn,xn; e] provided no free indeterminate in any of the fi's is

---

[+] In the following, e, f, g,... will denote lambda-expressions and x, y,... indeterminates. Unless stated otherwise, they are always assumed universally quantified in definitions and theorems of the meta-language.

[++] This rule will not be applicable to the lambda-expressions generated by the compiler.

bound in e.

Therefore the syntax of lambda-expressions will be extended by allowing a list of indeterminates in abstractions, viz.

(8) <binding indeterminates> ::= <binding indeterminates>,<indeterminate>

This notation can be viewed as a shorthand for nested abstractions:

(% x1,x2,...,xn: e) means (% x1:(% x2:(...(% xn: e)...))).

However, an automatic evaluator can use the above lemma for a faster substitution algorithm for lambda-expressions in this form.

1.3. Systems of Lambda-Expression Definitions

It is a convenient practice to define a certain name[+] to be a representative of a given lambda-expression. Then this name may be used many times without rewriting its whole definition. The following productions complete the syntax of the target language:

(9) <list of definitions> ::= <definition>
(10) <list of definitions> ::= <list of definitions><definition>
(11) <definition> ::= <name>=<lambda-expression>.
(12) <lambda-expression> ::= <name>
(13) <name> ::= <PASCAL-identifier including '$' in the letter set>

An "object"-program is then a <list of definitions>. At this point a single lambda-expression may not always be recovered by merely replacing all names by their corresponding lambda-expressions because some names could be referred recursively using their own names on right-hand sides of their definitions. Before this problem can be resolved, some basic lambda-expressions shall be introduced. Since the compiler generates source-program-dependent names, special or predefined names will always be distinguished from these by a preceeding '$' character. This is the reason for including a '$' sign to the PASCAL letter set in the productions (1) and (13).

[+] Names act like variables in the language. They are distinctly different from indeterminates in that the language does not contain any rules indicating what objects indeterminates represent or how they may "vary" throughout a calculation. By specifying theorems about the language, indeterminates often attain the property of meta-variables. Therefore "name" was chosen to avoid possible confusion.

$ID = (% X: X).
The identity ("do-nothing") function and empty list.

$CAT = (% X,Y: (% Z: ((X Z) Y))).
The concatenation of objects. If (% X: ((((X y1) y2) ...) yn)) represents a list of n elements $CAT will then append an element to a list of this structure.

$OMEGA = ((% X,Y: (X Y))(% X,Y: (X Y))).
The undefined value. It should be noted that ($OMEGA f) —> $OMEGA but $OMEGA does not possess a normal form.

$Y = (% X:((% Y:(X(Y Y)))(% Y:(X(Y Y))))).
The recursion operator. Since ($Y g) <—> (g ($Y g)), ($Y g) is a solution to the recursive definition of F = (g F), provided that g does not contain the name F.

$Y can now be employed to model general recursion. First it is necessary to beta-expand the right-hand sides of recursive definitions into the form

((((g <name>)<name>)...)<name>)

such that no name occurs inside the lambda-expression g and all recursively referenced names are listed in a given order. An explicit solution of the system of definitions

n1 = ((((g1 n1) n2)...) nk).
n2 = ((((g2 n1) n2)...) nk).
•
•
•
nk = ((((gk n1) n2)...) nk).

is determined by

ni ≡ ((((Y[i,k] g1) g2)...) gk), with

XZ-list ≡ (% Y:((... ((Y(X Z1))(X Z2)) ...)(X Zk))), and
Y[i,k] ≡ (% Z1,...,Zk:(($Y (% X: XZ-list))(% X1,...,Xk:Xi))).

This is also the least fixed point solution under a certain ordering [8]. However, it should be noted that an automatic evaluator will work more efficiently by replacing names recursively during execution time rather than introducing the $Y operator beforehand.

1.4. Primitives in the Model

It is possible to represent natural numbers and arithmetic operations in the lambda-calculus [4]. This representation can be extended also to (signed) integers and much of computer

arithmetic [1].

But instead of defining them as lambda-expressions, we accept a number of arithmetical and logical constants and operators as primitives in our model. The reduction characteristics of these primitives reflect the algebraic properties of the corresponding objects (viz. the integers and the logical values). An evaluator program can simulate these primitives with computer-internal arithmetic operations rather than using their lambda-calculus definitions, thus gaining a considerable gain in speed.

The compiled program may contain the following names associated with primitives:

0, 1, 2, ... The positive integers. These are the only names syntactically different from identifiers. n, m,... will denote lambda-expressions reducing to the integers n, m,... or their names.
$MINUSUNARY... Integer negation.
$PLUS..... Integer addition.
$MINUS..... Integer subtraction.
$MULT..... Integer multiplication.
$DIV..... Integer division.
$TRUE..... Boolean value true. It is assumed that (($TRUE g) h) —> g.
$FALSE..... Boolean value false. It is assumed that (($FALSE g) h) —> h.
$NOT..... Boolean negation.
$AND..... Boolean conjunction.
$OR..... Boolean disjunction.
$EQ..... Integer comparison equal.
$NE..... Integer comparison not equal.
$GT..... Integer comparison greater.
$GE..... Integer comparison greater than or equal to.
$LT..... Integer comparison less.
$LE..... Integer comparison less than or equal to.

The following three primitives are used for array handling. An n-dimensional PASCAL array is treated as a vector of n-1 dimensional arrays with 0 dimensional arrays treated as scalar objects. Vectors will be treated as lists in the object language (see $CAT). For the definition of these primitives in the lambda-calculus, see [1].

$TUPINIT..... Initialization of an array. Its reduction property is (...(($TUPINIT n) m1)... mn) —> "list of m1 lists of m2 lists of ... mn $OMEGAs".
$RETRIEVE..... Indexing of vector elements. Its reduction property is (f (($RETRIEVE i) k)) —> "i-th element of f if f is a list of k items (lambda-expressions)".

$REPLACE..... Assigning a vector element. Its reduction property is (f((($REPLACE i) k) g) —> "list of k items provided that f is a list of k elements where all but the i-th element are copied from f and the i-th position is g".

In the lambda-calculus, characters may be modelled by their corresponding numerical code. In order to distinguish the codes from numbers a primitive equivalent to the standard PASCAL function "CHR" is introduced:

CHR..... Code character. In the pure lambda-calculus CHR = $ID.

1.5. Functional Semantics of Variables and Statements

Each statement of a PASCAL program may be thought of as operateing on two different entities: A set of variables (global and local) addressable at the time the statement is being executed (its "environment"), and some sort of register indicating which place in the program is currently executed. It is not hard to imagine that this register may contain an eventually recursive description of the entire portion of the program not executed so far (the "continuation" or the "program remainder"). With this view a statement acts more like a functional since one of its arguments, the continuation, itself turns out to be a function. A statement can then be translated into an abstraction with respect to the continuation, denoted by the indeterminate "$PHI", and the environment variables, denoted by their PASCAL identifiers whenever possible. If imported and local identifiers coincide, conflicts will be resolved by appending "$" and the proper block level number to these identifiers. If all continuations and current values of variables are arranged in a certain list form, this abstraction will not become too complex to construct.

In the following, a representation rule [2] of the form

$$\{S\}/(v1, v2, \ldots, vn) \equiv \text{abstraction},$$

where S is a statement and (v1, v2,..., vn) is its environment, will be used to describe which kind of abstractions model these statements, and to give a more concise expression to the underlying ideas. As the compiler defines each abstraction of the statement i by the name "$STMi", representation rules can also be seen as patterns for these definitions. For a discussion of how representation rules are derived, see [2].

1.6. Compound Statements and Blocks

Compound statements are compositions of functions. This suggests the following representation rule:

```
{begin; S1;S2;...; Sn end}/E =
   (% $PHI:({S1}/E ({S2}/E (...({Sn}/E $PHI)...)))).
```

It should be noted that the program remainder of each Si is the first operand applied to the statement. Therefore -- and this is true for all representations -- a statement representation merely has to substitute this first operand into a place where it will become applicable after the statement's reduction is finished. In the following, the environments will not be explicitly specified if they stay the same throughout a representation rule.

Blocks introduce new (local) variables, initialize them to an undefined value and delete them from the environment after execution of their body. Let E be the global and F=(u1,..., um, v1,..., vn) be the local environment (identifier conflicts already resolved):

```
{var u1:<type1>;...; um:<typem>; begin S1;...; Sk end}/E =
   (% $PHI:(...((({S1}/F ({S2}/F (...({Sk}/F (% u1,...,um:$PHI))
   ...))){init u1}) {init u2})... {init um}));
where {init u} is $OMEGA if u is a scalar variable,
               is (($TUPINIT 1) p) if u is a vector of p items,
               is ((($TUPINIT 2) p1) p2) if u is a p1*p2 matrix,
                                  .
                                  .
                                  .
```

As a statement is translated into an abstraction of $PHI and the environment variables, all current values of these variables must follow the continuation before and also after the abstraction was reduced. It should be noted that an attempt to reference an undefined value will result in an infinite reduction sequence due to a property of $OMEGA.

1.7. Expressions and Assignments

So far the compilation of only integers and Boolean constants has been specified. But since scalar identifiers and characters can be identified with the ordinal numbers encoding them, all scalar constants suitable for lambda-calculus representation can be compiled. Entire variables are indeterminates of their own identifiers with ambiguities removed. As a slight restriction only unary and binary operators on scalar operands are accepted. Due to the list-like translation of arrays, records can be viewed as a special form of arrays and their field identifiers as indices.

Rational and real numbers are not treated here (see [1]). Literals and sets are part of PASCAL because they allow a very efficient implementation on a binary computer, but could be simulated in the lambda-calculus only by a rather clumsy representation. Also, pointer variables have been omitted since their representation will be quite complex. Files will be treated in section 1.8.

The representation rules for expressions (without function calls) heavily involve recursion. The most significant are sketched below. In some instances a nesting level number is used as a superscript on matching pairs of parentheses to make the rules more readable:

Since our model requires prefix operators, the following representation rules are essentially infix to prefix translations:

{<expr.1> <binary operator> <expr.2>} =
  (("primitive of binary oper." {<epr.1>}) {<expr.2}).

{<unary operator> <expression>} =
  ("primitive of unary oper." {<expression>}).

For arrays in list form, it is assumed that the index origin is at 1. Therefore the compiler has to translate all index references explicitly to this origin. Let v be an array [lb..hb], b an array [BOOLEAN] and d be an array [lb1..hb1, lb2..hb2]:

{v [<expression>] } =
  (v (^{1}(^{2}$RETRIEVE (^{3}($MINUS{<expression>}) lb-1^3)^2)hb-lb+1^1)).

{b [<expression>] } =
  (b (^{1}(^{2}$RETRIEVE (^{3}({<expression>} 1) 2^3)^2) 2^1)).

{d [<expr.1>, <expr.2>] } =
  ((^{1}d (^{2}(^{3}$RETRIEVE (^{4}($MINUS {<expr.1>}) lb1-1^4)^3)
  hb1-lb1+1^2)^1)(^{5}(^{6}$RETRIEVE (^{7}($MINUS {<expr.2>}) lb2-1^7)^6)
  hb2-lb2+1^5)).

•
•
•

In the following, CHR and ORD are the standard PASCAL functions on scalars:

{'<character>'} = (CHR "order of this character").
{CHR(<expression>)} = (CHR {<expression>}).
{ORD(<expression>)} = {<expression>}.

{-n} = ($MINUSUNARY n).

An assignment statement will be translated into a

substitution of the right-hand expression for the left-hand variable position in the list of corresponding indeterminates. Assignments to elements of an array complicate this process somewhat:

```
{vi:=<expression>}/E =
   (% $PHI, v1,..., vn: (...(((...(($PHI v1) v2)... vi-1)
   {<expression>}/E) vi+1)... vn).

{v [<expr.1>] := <expr.2>}/E =
   (% $PHI, v1,..., vn: (...(((...(($PHI v1) v2)... vj-1)
   (1v (2(3(4$REPLACE (5($MINUS{<expr.1>}/E}) lb-1 5)4)hb-lb+1 3)
   {<expr.2>}/E}2)1)) vj+1)... vn).

{d [<expr.1>, <expr.2>] := <expr.3>}/E =
   (% $PHI, v1,..., vn: (...(((...(($PHI v1) v2)... vk-1)
   assign) vk+1)... vn);
where assign is the lambda-expression:
   (d(0(1(2$REPLACE (3($MINUS {<expr.1>}/E) lb1-1 3)2) hb1-lb+1 1)
   (4(5d (6(7$RETRIEVE (8($MINUS {<expr.1>}/E) lb1-1 8)7)
   hb1-lb1+1 6)5) (9(10(11$REPLACE (12($MINUS {<expr.2>}/E)
   lb2-1 12)11) hb2-lb2+1 10) {<expr.3>}/E 9) 4)0)).
                              •
                              •
                              •
```

1.8. Files and Input-Output

As the I/O facilities in the lambda-calculus model are rather simple, only the two standard files INPUT and OUTPUT are supported during compilation. These files are unlike standard PASCAL files of INTEGER. Their representations in lambda-calculus are naturally lists denoted by the indeterminate $SCARDS for INPUT and $SPRINT for OUTPUT. Their initial values are all input items coded as lambda-expressions for $SCARDS and $ID (the empty list) for $SPRINT. The current file pointers INPUT@ and OUTPUT@ will be treated as integer indeterminates of the same name ("@" omitted). Furthermore, only the two predefined I/O routines GET and PUT are accepted by the code generation routines of the compiler. Upon call, data is transferred between the files and their associated file pointers. Contrary to standard PASCAL the input file is not automatically reset which means that INPUT@ contains $OMEGA at the beginning of a program and not the first data integer of $SCARDS.

In the following representation rules, one should notice that INPUT and OUTPUT are automatically adjoined to the environment G=(v1,..., vn, INPUT, OUTPUT) of a statement if their corresponding files appear in the program head:

```
{ GET }/G =
   (% $PHI, v1,..., vn, OUTPUT, INPUT:(% $SCARDS, $SPRINT:
   ((((...(($PHI v1) v2)... vn) OUTPUT) $SCARDS) $SPRINT))).

{ PUT }/G =
   (% $PHI, v1,..., vn, OUTPUT, INPUT:(% $SPRINT:((((...(($PHI
   v1) v2)... vn) OUTPUT) INPUT) (($CAT $SPRINT) OUTPUT)))).
```

These representations only require $SPRINT to be arranged in list format (see definition of $CAT) whereas the input elements merely have to follow this output list. The representation of a complete program which the compiler names $PROGRAM follows:

{program...; Si.}/() = (({Si}/() $ID)$ID);
where Si is the outermost begin-end pair and () the empty list.

The first $ID is the final program remainder and the second the empty $SPRINT. $PROGRAM has the property that

(($PROGRAM i1)... ip) ⟶ (% X:((X o1)... oq))

where o1,..., oq are the output numbers which would be obtained by executing the program on the input numbers i1,..., ip.

1.9. Example#1

The following sample program illustrates all the concepts described so far. The statement numbers listed will be referred within the generated code later on:

```
Stmnr     Source code:
-----     ------------
          (*$U+,X- superscripts, no cross reference *)
          PROGRAM EXAMPLE1(INPUT, OUTPUT);
          CONST
              LB=2; HB=5; (* bounds for V *)
              LB1=-3; HB1=0;
              LB2=0; HB2=5; (* bounds for D *)
          TYPE
              SC=(ONE,TWO,THREE);
              LET='A'..'Z';
          VAR
              I: INTEGER; C: LET; S: SC;
              V: ARRAY[LB..HB] OF INTEGER;
              B: ARRAY[BOOLEAN] OF TWO..THREE;
              D: ARRAY[LB1..HB1, LB2..HB2] OF CHAR;
              (* 3 dimensions! *)
              P: ARRAY[LET, SC] OF ARRAY[2..7] OF TRUE..FALSE;
          BEGIN
             (* The following statements make no sense *)
             (* but illustrate the compilation         *)
   3         GET; I:=INPUT@;
```

```
 4          V[I+1]:=-(I+1);
 5          I:=I+V[ (LB+HB) DIV 2 ] * I;
 7          OUTPUT@:=V[4]; PUT;
 8          B[FALSE]:=THREE;
 9          S:=B[ NOT(I<>0) AND (V[I]<I+1) ];
10          BEGIN
11             D[-2, I*2]:= 'Q';
12             C:=D[HB1-2] [V[3]]
12          END;
12          (* some difficult assignments *)
13          P[C,S,I]:=(I<=2) OR (C='B');
14          B[P[C,S,I]]:=TWO
14       END.
```

The compiler generated the following code. Optionally, matching parentheses are identified by superscripts. An asteriks in column one signals a comment line and this line should be ignored by automatic evaluators.

```
* LAMBDA CODE FOR EXAMPLE1

$STM2=(11% $PHI,P,D,B,V,S,C,I,OUTPUT,INPUT:(10% $SPRINT,$SCARDS:
(9(8(7(6(5(4(3(2(1(0$PHI P0)D1)B2)V3)S4)C5)I6)OUTPUT7)$SCARDS8)$
SPRINT9)10)11).

$STM3=(9% $PHI,P,D,B,V,S,C,I,OUTPUT,INPUT:(8(7(6(5(4(3(2(1(0$PHI
 P0)D1)B2)V3)S4)C5)INPUT6)OUTPUT7)INPUT8)9).

$STM4=(14% $PHI,P,D,B,V,S,C,I,OUTPUT,INPUT:(13(12(11(10(9(8(2(1(
0$PHI P0)D1)B2)(7V(6(5(4$REPLACE (3(2$MINUS (1(0$PLUS I0)11)2)13
)4)45)(2$MINUSUNARY (1(0$PLUS I0)11)2)6)7)8)S9)C10)I11)OUTPUT12)
INPUT13)14).

$STM5=(15% $PHI,P,D,B,V,S,C,I,OUTPUT,INPUT:(14(13(12(5(4(3(2(1(0
$PHI P0)D1)B2)V3)S4)C5)(11(0$PLUS I0)(10(9$MULT (8V(7(6$RETRIEVE
 (5(4$MINUS (3(2$DIV (1(0$PLUS 20)51)2)23)4)15)6)47)8)9)I10)11)1
2)OUTPUT13)INPUT14)15).

$STM6=(9% $PHI,P,D,B,V,S,C,I,OUTPUT,INPUT:(8(7(6(5(4(3(2(1(0$PHI
 P0)D1)B2)V3)S4)C5)I6)(4V(3(2$RETRIEVE (1(0$MINUS 40)11)2)43)4)7
)INPUT8)9).

$STM7=(11% $PHI,P,D,B,V,S,C,I,OUTPUT,INPUT:(10% $SPRINT:(9(8(7(6
(5(4(3(2(1(0$PHI P0)D1)B2)V3)S4)C5)I6)OUTPUT7)INPUT8)(($CAT $SPR
INT)OUTPUT)9)10)11).

$STM8=(13% $PHI,P,D,B,V,S,C,I,OUTPUT,INPUT:(12(11(10(9(8(7(6(1(0
$PHI P0)D1)(5B(4(3(2$REPLACE (1(0$FALSE 10)21)2)23)24)5)6)V7)S8)
C9)I10)OUTPUT11)INPUT12)13).
```

```
$STM9=(18% $PHI,P,D,B,V,S,C,I,OUTPUT,INPUT:(17(16(15(14(13(3(2(1
(0$PHI P0)D1)B2)V3)(12B(11(10$RETRIEVE (9(8(7(3$AND (2$NOT (1(0$
NE I0)O1)2)3)(6(5$LT (4V(3(2$RETRIEVE (1(0$MINUS I0)11)2)43)4)5)
(1(0$PLUS I0)11)6)7) 18)29)10)211)12)13)C14)I15)OUTPUT16)INPUT17
)18).

$STM11=(18% $PHI,P,D,B,V,S,C,I,OUTPUT,INPUT:(17(16(15(14(13(12(1
1(10(0$PHI P0)(9D(8(4(3$REPLACE (2(1$MINUS (0$MINUSUNARY 20)1)(0
$MINUSUNARY 40)2)3)44)(7(5D(4(3$RETRIEVE (2(1$MINUS (0$MINUSUNAR
Y 20)1)(0$MINUSUNARY 40)2)3)44)5)(6(5(4$REPLACE (3(2$MINUS (1(0$
MULT I0)21)2)(0$MINUSUNARY 10)3)4)65)(0CHR 2160)6)7)8)9)10)B11)V
12)S13)C14)I15)OUTPUT16)INPUT17)18).

$STM12=(14% $PHI,P,D,B,V,S,C,I,OUTPUT,INPUT:(13(12(11(10(4(3(2(1
(0$PHI P0)D1)B2)V3)S4)(9(6D(5(4$RETRIEVE (3(2$MINUS (1(0$MINUS O
0)21)2)(0$MINUSUNARY 40)3)4)45)6)(8(7$RETRIEVE (6(5$MINUS (4V(3(
2$RETRIEVE (1(0$MINUS 30)11)2)43)4)5)(0$MINUSUNARY 10)6)7)68)9)1
0)I11)OUTPUT12)INPUT13)14).

$STM10=(2% $PHI:(1$STM11(0$STM12 $PHI0)1)2).

$STM13=(20% $PHI,P,D,B,V,S,C,I,OUTPUT,INPUT:(19(18(17(16(15(14(1
3(12(11$PHI (10P(9(3(2$REPLACE (1(0$MINUS C0)1921)2)413)(8(4P(3(
2$RETRIEVE (1(0$MINUS C0)1921)2)413)4)(7(1(0$REPLACE S0)21)(6(5(
4P(3(2$RETRIEVE (1(0$MINUS C0)1921)2)413)4)(1(0$RETRIEVE S0)21)5
)(4(3(2$REPLACE (1(0$MINUS I0)11)2)63)(3(2$OR (1(0$LE I0)21)2)(1
(0$EQ C0)(0CHR 1940)1)3)4)6)7)8)9)10)11)D12)B13)V14)S15)C16)I17)
OUTPUT18)INPUT19)20).

$STM14=(20% $PHI,P,D,B,V,S,C,I,OUTPUT,INPUT:(19(18(17(16(15(14(1
3(1(0$PHI P0)D1)(12B(11(10(9$REPLACE (8(7(6(5(4P(3(2$RETRIEVE (1
(0$MINUS C0)1921)2)413)4)(1(0$RETRIEVE S0)21)5)(3(2$RETRIEVE (1(
0$MINUS I0)11)2)63)6) 17)28)9)210)111)12)13)V14)S15)C16)I17)OUTP
UT18)INPUT19)20).

$STM1=(12% $PHI:((((((((((11$STM2(10$STM3(9$STM4(8$STM5(7$STM6(6
$STM7(5$STM8(4$STM9(3$STM10(2$STM13(1$STM14(0% P,D,B,V,S,C,I,OUT
PUT,INPUT:$PHI0)1)2)3)4)5)6)7)8)9)10)11)(3(2(1(0$TUPINIT 30)411)
22)63))(2(1(0$TUPINIT 20)411)62))(1(0$TUPINIT 10)21))(1(0$TUPINIT
 10)411))$OMEGA)$OMEGA)$OMEGA)$OMEGA)$OMEGA)12).

$PROGRAM=(($STM1 $ID)$ID).
```

1.10. Conditional Statements

The reduction properties of $TRUE and $FALSE mentioned earlier, together with the definition $IF=$ID, imply a straightforward representation of if-statements:

{if <expression> then S1 else S2}/E =
(% $PHI, v1,..., vn: (...(((((($IF {<expression>}/E) {S1}/E)
{S2}/E) $PHI) v1)... vn).

{if <expression> then S1}/E =
(% $PHI, v1,..., vn: (...(((((($IF {<expression>}/E) {S1}/E)
$ID) $PHI) v1)... vn).

Case-statements could be represented as a sequence of if-statements.

1.11. Repetitive Statements

Any PASCAL loop can be transformed into a while loop. For instance repeat S until <expression> is equivalent to begin S; while <expression> do S end. While-statements themselves lead to recursive definitions. Let i be the statement number of the loop being represented:

{while <expression> do S}/E =
$STMi=(% $PHI, v1,..., vn:(...(((^{1}(^{2}(^{3}$IF {<expression>}/E^3)
(^{4}{S}/E (^{5}$STMi $PHI^5)^4)^2) $PHI^1) v1)... vn). .

The small but essential difference between this if-construction and the one in the previous section 1.10 should be observed: The alternate clause has to be $PHI instead of $ID.

1.12. Example#2

The following program illustrates compilation of while loops and if statements:

```
Stmnr     Source code:
-----     ------------
          (*$U+,X- superscripts, no cross reference *)
          PROGRAM SORT(INPUT, OUTPUT);
          CONST LB=4; HB=9;
          VAR A: ARRAY[LB..HB] OF INTEGER;
              I, J, TEMP: INTEGER;
              NC: BOOLEAN;
          BEGIN
   2         I:=LB;
   3         WHILE (I<=HB) DO
   3            BEGIN
   5               GET;
   6               A[I]:=INPUT@
   6            END;
   7         J:=HB;
   8         NC:=FALSE;
   9         WHILE (J>LB) AND NOT NC DO
   9            BEGIN
  11               I:=LB;
```

```
 12                NC:=TRUE;
 13                WHILE (I<J) DO
 14                   BEGIN
 15                      IF A[I]>A[I+1]
 15                         THEN BEGIN
 17                                 TEMP:=A[I];
 18                                 A[I]:=A[I+1];
 19                                 A[I+1]:=TEMP;
 20                                 NC:=FALSE
 20                               END;
 21                      I:=I+1
 21                   END;
 22                J:=J-1
 22             END;
 23          I:=LB;
 24          WHILE (I<=HB) DO
 24             BEGIN
 26                OUTPUT@:=A[I];
 26                PUT
 27             END
 27       END.
```

* LAMBDA CODE FOR SORT

```
$STM2=(7% $PHI,NC,TEMP,J,I,A,OUTPUT,INPUT:(6(5(4(3(2(1(0$PHI NC0
)TEMP1)J2)43)A4)OUTPUT5)INPUT6)7).

$STM5=(9% $PHI,NC,TEMP,J,I,A,OUTPUT,INPUT:(8% $SPRINT,$SCARDS:(7
(6(5(4(3(2(1(0$PHI NC0)TEMP1)J2)I3)A4)OUTPUT5)$SCARDS6)$SPRINT7)
8)9).

$STM6=(9% $PHI,NC,TEMP,J,I,A,OUTPUT,INPUT:(8(7(6(3(2(1(0$PHI NC0
)TEMP1)J2)I3)(5A(4(3(2$REPLACE (1(0$MINUS I0)31)2)63)INPUT4)5)6)
OUTPUT7)INPUT8)9).

$STM4=(2% $PHI:(1$STM5(0$STM6 $PHI0)1)2).

$STM3=(12% $PHI,NC,TEMP,J,I,A,OUTPUT,INPUT:(11(10(9(8(7(6(5(4(3(
2$IF(1(0$LE I0)91)2)(1$STM4(0$STM3 $PHI0)1)3)$PHI4)NC5)TEMP6)J7)
I8)A9)OUTPUT10)INPUT11)12).

$STM7=(7% $PHI,NC,TEMP,J,I,A,OUTPUT,INPUT:(6(5(4(3(2(1(0$PHI NC0
)TEMP1)92)I3)A4)OUTPUT5)INPUT6)7).

$STM8=(7% $PHI,NC,TEMP,J,I,A,OUTPUT,INPUT:(6(5(4(3(2(1(0$PHI $FA
LSE0)TEMP1)J2)I3)A4)OUTPUT5)INPUT6)7).

$STM11=(7% $PHI,NC,TEMP,J,I,A,OUTPUT,INPUT:(6(5(4(3(2(1(0$PHI NC
0)TEMP1)J2)43)A4)OUTPUT5)INPUT6)7).
```

```
$STM12=(7% $PHI,NC,TEMP,J,I,A,OUTPUT,INPUT:(6(5(4(3(2(1(0$PHI $T
RUE0)TEMP1)J2)I3)A4)OUTPUT5)INPUT6)7).

$STM17=(11% $PHI,NC,TEMP,J,I,A,OUTPUT,INPUT:(10(9(8(7(6(5(0$PHI
NC0)(4A(3(2$RETRIEVE (1(0$MINUS I0)31)2)63)4)5)J6)I7)A8)OUTPUT9)
INPUT10)11).

$STM18=(12% $PHI,NC,TEMP,J,I,A,OUTPUT,INPUT:(11(10(9(3(2(1(0$PHI
 NC0)TEMP1)J2)I3)(8A(7(3(2$REPLACE (1(0$MINUS I0)31)2)63)(6A(5(4
$RETRIEVE (3(2$MINUS (1(0$PLUS I0)11)2)33)4)65)6)7)8)9)OUTPUT10)
INPUT11)12).

$STM19=(11% $PHI,NC,TEMP,J,I,A,OUTPUT,INPUT:(10(9(8(3(2(1(0$PHI
NC0)TEMP1)J2)I3)(7A(6(5(4$REPLACE (3(2$MINUS (1(0$PLUS I0)11)2)3
3)4)65)TEMP6)7)8)OUTPUT9)INPUT10)11).

$STM20=(7% $PHI,NC,TEMP,J,I,A,OUTPUT,INPUT:(6(5(4(3(2(1(0$PHI $F
ALSE0)TEMP1)J2)I3)A4)OUTPUT5)INPUT6)7).

$STM16=(4% $PHI:(3$STM17(2$STM18(1$STM19(0$STM20 $PHI0)1)2)3)4).

$STM15=(19% $PHI,NC,TEMP,J,I,A,OUTPUT,INPUT:(18(17(16(15(14(13(1
2(11(10(9(8$IF(7(5$GT (4A(3(2$RETRIEVE (1(0$MINUS I0)31)2)63)4)5
)(6A(5(4$RETRIEVE (3(2$MINUS (1(0$PLUS I0)11)2)33)4)65)6)7)8)$ST
M169)$ID10)$PHI11)NC12)TEMP13)J14)I15)A16)OUTPUT17)INPUT18)19).

$STM21=(7% $PHI,NC,TEMP,J,I,A,OUTPUT,INPUT:(6(5(4(3(2(1(0$PHI NC
0)TEMP1)J2)(1(0$PLUS I0)11)3)A4)OUTPUT5)INPUT6)7).

$STM14=(2% $PHI:(1$STM15(0$STM21 $PHI0)1)2).

$STM13=(12% $PHI,NC,TEMP,J,I,A,OUTPUT,INPUT:(11(10(9(8(7(6(5(4(3
(2$IF(1(0$LT I0)J1)2)(1$STM14(0$STM13 $PHI0)1)3)$PHI4)NC5)TEMP6)
J7)I8)A9)OUTPUT10)INPUT11)12).

$STM22=(7% $PHI,NC,TEMP,J,I,A,OUTPUT,INPUT:(6(5(4(3(2(1(0$PHI NC
0)TEMP1)(1(0$MINUS J0)11)2)I3)A4)OUTPUT5)INPUT6)7).

$STM10=(4% $PHI:(3$STM11(2$STM12(1$STM13(0$STM22 $PHI0)1)2)3)4).

$STM9=(14% $PHI,NC,TEMP,J,I,A,OUTPUT,INPUT:(13(12(11(10(9(8(7(6(
5(4$IF(3(2$AND (1(0$GT J0)41)2)(0$NOT NC0)3)4)(1$STM10(0$STM9 $P
HI0)1)5)$PHI6)NC7)TEMP8)J9)I10)A11)OUTPUT12)INPUT13)14).

$STM23=(7% $PHI,NC,TEMP,J,I,A,OUTPUT,INPUT:(6(5(4(3(2(1(0$PHI NC
0)TEMP1)J2)43)A4)OUTPUT5)INPUT6)7).
```

```
$STM26=(7% $PHI,NC,TEMP,J,I,A,OUTPUT,INPUT:(6(5(4(3(2(1(0$PHI NC
0)TEMP1)J2)I3)A4)(4A(3(2$RETRIEVE (1(0$MINUS I0)31)2)63)4)5)INPU
T6)7).

$STM27=(9% $PHI,NC,TEMP,J,I,A,OUTPUT,INPUT:(8% $SPRINT:(7(6(5(4(
3(2(1(0$PHI NC0)TEMP1)J2)I3)A4)OUTPUT5)INPUT6)(($CAT $SPRINT)OUT
PUT)7)8)9).

$STM25=(2% $PHI:(1$STM26(0$STM27 $PHI0)1)2).

$STM24=(12% $PHI,NC,TEMP,J,I,A,OUTPUT,INPUT:(11(10(9(8(7(6(5(4(3
(2$IF(1(0$LE I0)91)2)(1$STM25(0$STM24 $PHI0)1)3)$PHI4)NC5)TEMP6)
J7)I8)A9)OUTPUT10)INPUT11)12).

$STM1=(8% $PHI:(((((((((7$STM2(6$STM3(5$STM7(4$STM8(3$STM9(2$STM2
3(1$STM24(0% NC,TEMP,J,I,A,OUTPUT,INPUT:$PHI0)1)2)3)4)5)6)7)$OME
GA)$OMEGA)$OMEGA)$OMEGA)(1(0$TUPINIT 10)61))$OMEGA)$OMEGA)8).

$PROGRAM=(($STM1 $ID)$ID).
```

1.13. Procedures

The full modelling of procedures containing different kinds of parameter references (call by name, value, reference), global side effects and possible recursive invocations constitutes a major challenge to functional semantics [1,2]. Indeed, the actual implementations are fairly involved. At this state of development, only procedures with parameters passed by value are accepted by the code generation part of the compiler, but side-effects and recursive calls are permitted. This type of procedure will henceforth be referred to as a "V-procedure".

V-procedure definitions will be represented by names for blocks, and their parameters will be initialized dynamically with the argument values passed:

```
{V-procedure p(a1:<type1>;...; ak:<typek>); <block>}/E =
   p = (% $VAL$a1,..., $VAL$ak: {<block>}/E). .
```

Inside the block representation (see section 1.6) a new initial value is chosen for all formal parameters ai:

{init ai} is VALai for all value parameters ai.

In the case that the environments of the calling statement and the V-procedure definition are the same, the representation of the call is simple:

```
{ p (<expr.1>,..., <expr.k>) }/E =
   (% $PHI, v1,..., vn:(...(((...(p {<expr.1>}/E)...
   {<expr.k>}/E) $PHI) v1)... vn)).
```

Should the environments differ (e.g. if the V-procedure is called recursively), all additional variables of the calling environment have to be disposed of during the V-procedure execution and recovered upon return. This is done by including them into the continuation of the calling statement and re-establishing them when this continuation is accessed by the reduction process. Let G=(u1,..., um, v1,..., vn) be the calling and E=(v1,..., vn) the procedure environments.

```
{ p (<expr.1>,..., <expr.k>) }/G =
   (% $PHI, u1,..., um, v1,..., vn:(...(((...(p {<expr.1>}/E)...
   {<expr.k>}/E)(...(($PHI u1) u2)... um)) v1)... vn)).
```

This representation solves the so-called environment conflict problem [2].

1.14. Example#3

The following example shows how procedures and their calls will be translated:

```
Stmnr      Source code:
-----      ------------
           (*$U+,X- superscripts, no cross reference *)
           PROGRAM EXAMPLE3(OUTPUT);
              VAR I, J: INTEGER;
              PROCEDURE P1(K, L: INTEGER);
                 VAR M: INTEGER;
                 BEGIN
   2                IF 0<>L
   2                   THEN BEGIN
   6                           M:=K; K:=L; L:=M MOD L;
   7                           P1(K, L)
                            END
   8                   ELSE OUTPUT@:=K
   8             END; (* P1 *)
   8          PROCEDURE GCD(I, J: INTEGER);
  11             BEGIN P1(I, J); END; (* GCD *)
  11         BEGIN
  14            I:=28; J:=7;
  15            GCD(I, J+14);
  15            PUT
  16         END.
```

```
* LAMBDA CODE FOR EXAMPLE3

P1=(0% $VAL$L,$VAL$K:$STM10).

$STM4=(6% $PHI,M,K,L,J,I,OUTPUT:(5(4(3(2(1(0$PHI K0)K1)L2)J3)I4)
OUTPUT5)6).

$STM5=(6% $PHI,M,K,L,J,I,OUTPUT:(5(4(3(2(1(0$PHI M0)L1)L2)J3)I4)
OUTPUT5)6).

$STM6=(6% $PHI,M,K,L,J,I,OUTPUT:(5(4(3(2(1(0$PHI M0)K1)(1(0$MOD
M0)L1)2)J3)I4)OUTPUT5)6).

$STM7=(7% $PHI,M,K,L,J,I,OUTPUT:(6(5(4(3(1(0P1 K0)L1)(2(1(0$PHI
M0)K1)L2)3)J4)I5)OUTPUT6)7).

$STM3=(4% $PHI:(3$STM4(2$STM5(1$STM6(0$STM7 $PHI0)1)2)3)4).

$STM8=(6% $PHI,M,K,L,J,I,OUTPUT:(5(4(3(2(1(0$PHI M0)K1)L2)J3)I4)
K5)6).

$STM2=(12% $PHI,M,K,L,J,I,OUTPUT:(11(10(9(8(7(6(5(4(3(2$IF (1(0$
NE 00)L1)2)$STM33)$STM84)$PHI5)M6)K7)L8)J9)I10)OUTPUT11)12).

$STM1=(2% $PHI:((((1$STM2(0% M,K,L:$PHI0)1)$OMEGA)$VAL$K)$VAL$L)
2).

GCD=(0% $VAL$J$2,$VAL$I$2:$STM90).

$STM10=(6% $PHI,I$2,J$2,J$1,I$1,OUTPUT:(5(4(3(2(1(0P1 I$20)J$21)
(1(0$PHI I$20)J$21)2)J$13)I$14)OUTPUT5)6).

$STM11=$ID.

$STM9=(3% $PHI:(((2$STM10(1$STM11(0% I$2,J$2:$PHI0)1)2)$VAL$I$2)
$VAL$J$2)3).

$STM13=(3% $PHI,J,I,OUTPUT:(2(1(0$PHI J0)281)OUTPUT2)3).

$STM14=(3% $PHI,J,I,OUTPUT:(2(1(0$PHI 70)I1)OUTPUT2)3).

$STM15=(7% $PHI,J,I,OUTPUT:(6(5(4(3(2(0GCD I0)(1(0$PLUS J0)141)2
)$PHI 3)J4)I5)OUTPUT6)7).

$STM16=(5% $PHI,J,I,OUTPUT:(4% $SPRINT:(3(2(1(0$PHI J0)I1)OUTPUT
2)(($CAT $SPRINT)OUTPUT)3)4)5).

$STM12=(5% $PHI:((((4$STM13(3$STM14(2$STM15(1$STM16(0% J,I,OUTPU
T:$PHI0)1)2)3)4)$OMEGA)$OMEGA)$OMEGA)5).

$PROGRAM=(($STM12 $ID)$ID).
```

1.15. Remarks on Further Language Constructs

Until now all representations described have been actually implemented in the compiler. Some remarks are in order regarding how some PASCAL features for which no lambda code is currently generated by the compiler could be translated.

Labels can be viewed as names for continuations. A goto statement then merely substitutes the representation of the referenced label for the current program remainder. However, it seems a very tedious task to determine the continuation at a given point of a program at compilation time.

Function calls are similar to procedure calls. If no side effects occur their represention is actually very simple [2]. Otherwise many intermediate results have to be introduced because function calls can be made repeatedly within a single expression. Their representation is not theoretically difficult but it is rather hard to actually implement their translation.

The modelling of procedure and function parameters as well as pointer variables seems too complicated at this stage.

1.16. Example#4

Part 1 is concluded with a "real" PASCAL program example to multiply matrices:

```
Stmnr     Source code:
-----     ------------
          (*$U+,X- superscripts, no cross reference *)
          PROGRAM MATRIXMULT(INPUT, OUTPUT);
             CONST LB=5; HB=10;
             TYPE RANGE=LB..HB;
                  MATRIX=ARRAY[RANGE, RANGE] OF INTEGER;
             VAR A, B, C: MATRIX;
                 I, J, K: INTEGER;

             PROCEDURE READWRITE(SWITCH: BOOLEAN; C: MATRIX);
             (* Reads in A and B (global) or prints C *)
             (* according to the logical SWITCH       *)
                VAR I, J: INTEGER;
                BEGIN
  2                I:=LB;
  3                WHILE I<=HB DO
  3                   BEGIN
  5                      J:=LB;
  6                      WHILE J<=HB DO
  6                         BEGIN
  8                            IF SWITCH
```

```
 8                                  THEN BEGIN
11                                        GET; A[I, J]:=INPUT@;
13                                        GET; B[I, J]:=INPUT@
13                                     END
13                                  ELSE BEGIN
15                                        OUTPUT@:=C[I][J]; PUT
16                                     END;
17                               J:=J+1
17                            END;
18                         I:=I+1
18                      END
18                END; (*READWRITE*)
18
18          BEGIN (* of main program *)
20             READWRITE(TRUE, C); (* C is just dummy *)
21             I:=LB;
22             WHILE (I<=HB) DO
22                BEGIN
24                   J:=LB;
25                   WHILE (J<=HB) DO
25                      BEGIN
27                         C[I, J]:=0;
28                         K:=LB;
29                         WHILE (K<=HB) DO
29                            BEGIN
31                               C[I,J]:=C[I,J]+A[I,K]*B[K,J];
32                               K:=K+1
32                            END;
33                         J:=J+1
33                      END;
34                   I:=I+1
34                END;
35             READWRITE(FALSE, C)
35          END.
```

```
* LAMBDA CODE FOR MATRIXMULT

READWRITE=(⁰% $VAL$SWITCH,$VAL$C$2:$STM1⁰).

$STM2=(¹²% $PHI,J$2,I$2,C$2,SWITCH,K,J$1,I$1,C$1,B,A,OUTPUT,INPU
T:(¹¹(¹⁰(⁹(⁸(⁷(⁶(⁵(⁴(³(²(¹(⁰$PHI J$2⁰)5¹)C$2²)SWITCH³)K⁴)J$1⁵)I$
1⁶)C$1⁷)B⁸)A⁹)OUTPUT¹⁰)INPUT¹¹)¹²).

$STM5=(¹²% $PHI,J$2,I$2,C$2,SWITCH,K,J$1,I$1,C$1,B,A,OUTPUT,INPU
T:(¹¹(¹⁰(⁹(⁸(⁷(⁶(⁵(⁴(³(²(¹(⁰$PHI 5⁰)I$2¹)C$2²)SWITCH³)K⁴)J$1⁵)I$
1⁶)C$1⁷)B⁸)A⁹)OUTPUT¹⁰)INPUT¹¹)¹²).
```

```
$STM10=(14% $PHI,J$2,I$2,C$2,SWITCH,K,J$1,I$1,C$1,B,A,OUTPUT,INP
UT:(13% $SPRINT,$SCARDS:(12(11(10(9(8(7(6(5(4(3(2(1(0$PHI J$20)I
$21)C$22)SWITCH3)K4)J$15)I$16)C$17)B8)A9)OUTPUT10)$SCARDS11)$SPR
INT12)13)14).

$STM11=(12% $PHI,J$2,I$2,C$2,SWITCH,K,J$1,I$1,C$1,B,A,OUTPUT,INP
UT:(11(10(9(8(7(6(5(4(3(2(1(0$PHI J$20)I$21)C$22)SWITCH3)K4)J$15
)I$16)C$17)B8)(7A(6(3(2$REPLACE (1(0$MINUS I$20)41)2)63)(5(4A(3(
2$RETRIEVE (1(0$MINUS I$20)41)2)63)4)(4(3(2$REPLACE (1(0$MINUS J
$20)41)2)63)INPUT4)5)6)7)9)OUTPUT10)INPUT11)12).

$STM12=(14% $PHI,J$2,I$2,C$2,SWITCH,K,J$1,I$1,C$1,B,A,OUTPUT,INP
UT:(13% $SPRINT,$SCARDS:(12(11(10(9(8(7(6(5(4(3(2(1(0$PHI J$20)I
$21)C$22)SWITCH3)K4)J$15)I$16)C$17)B8)A9)OUTPUT10)$SCARDS11)$SPR
INT12)13)14).

$STM13=(12% $PHI,J$2,I$2,C$2,SWITCH,K,J$1,I$1,C$1,B,A,OUTPUT,INP
UT:(11(10(9(8(7(6(5(4(3(2(1(0$PHI J$20)I$21)C$22)SWITCH3)K4)J$15
)I$16)C$17)(7B(6(3(2$REPLACE (1(0$MINUS I$20)41)2)63)(5(4B(3(2$R
ETRIEVE (1(0$MINUS I$20)41)2)63)4)(4(3(2$REPLACE (1(0$MINUS J$20
)41)2)63)INPUT4)5)6)7)8)A9)OUTPUT10)INPUT11)12).

$STM9=(4% $PHI:(3$STM10(2$STM11(1$STM12(0$STM13 $PHI0)1)2)3)4).

$STM15=(12% $PHI,J$2,I$2,C$2,SWITCH,K,J$1,I$1,C$1,B,A,OUTPUT,INP
UT:(11(10(9(8(7(6(5(4(3(2(1(0$PHI J$20)I$21)C$22)SWITCH3)K4)J$15
)I$16)C$17)B8)A9)(5(4C$2(3(2$RETRIEVE (1(0$MINUS I$20)41)2)63)4)
(3(2$RETRIEVE (1(0$MINUS J$20)41)2)63)5)10)INPUT11)12).

$STM16=(14% $PHI,J$2,I$2,C$2,SWITCH,K,J$1,I$1,C$1,B,A,OUTPUT,INP
UT:(13% $SPRINT:(12(11(10(9(8(7(6(5(4(3(2(1(0$PHI J$20)I$21)C$22
)SWITCH3)K4)J$15)I$16)C$17)B8)A9)OUTPUT10)INPUT11)((CAT $SPRINT
)OUTPUT)12)13)14).

$STM14=(2% $PHI:(1$STM15(0$STM16 $PHI0)1)2).

$STM8=(16% $PHI,J$2,I$2,C$2,SWITCH,K,J$1,I$1,C$1,B,A,OUTPUT,INPU
T:(15(14(13(12(11(10(9(8(7(6(5(4(3(2(1(0$IF SWITCH0)$STM91)$STM1
42)$PHI3)J$24)I$25)C$26)SWITCH7)K8)J$19)I$110)C$111)B12)A13)OUTP
UT14)INPUT15)16).

$STM17=(14% $PHI,J$2,I$2,C$2,SWITCH,K,J$1,I$1,C$1,B,A,OUTPUT,INP
UT:(13(12(11(10(9(8(7(6(5(4(3(2$PHI (1(0$PLUS J$20)11)2)I$23)C$2
4)SWITCH5)K6)J$17)I$18)C$19)B10)A11)OUTPUT12)INPUT13)14).
```

```
$STM7=(2% $PHI:(1$STM8(0$STM17 $PHI0)1)2).

$STM6=(17% $PHI,J$2,I$2,C$2,SWITCH,K,J$1,I$1,C$1,B,A,OUTPUT,INPU
T:(16(15(14(13(12(11(10(9(8(7(6(5(4(3(2$IF (1(0$LE J$20)101)2)(1
$STM7(0$STM6 $PHI0)1)3)$PHI4)J$25)I$26)C$27)SWITCH8)K9)J$110)I$1
11)C$112)B13)A14)OUTPUT15)INPUT16)17).

$STM18=(13% $PHI,J$2,I$2,C$2,SWITCH,K,J$1,I$1,C$1,B,A,OUTPUT,INP
UT:(12(11(10(9(8(7(6(5(4(3(2(0$PHI J$20)(1(0$PLUS I$20)11)2)C$23
)SWITCH4)K5)J$16)I$17)C$18)B9)A10)OUTPUT11)INPUT12)13).

$STM4=(3% $PHI:(2$STM5(1$STM6(0$STM18 $PHI0)1)2)3).

$STM3=(17% $PHI,J$2,I$2,C$2,SWITCH,K,J$1,I$1,C$1,B,A,OUTPUT,INPU
T:(16(15(14(13(12(11(10(9(8(7(6(5(4(3(2$IF (1(0$LE I$20)101)2)(1
$STM4(0$STM3 $PHI0)1)3)$PHI4)J$25)I$26)C$27)SWITCH8)K9)J$110)I$1
11)C$112)B13)A14)OUTPUT15)INPUT16)17).

$STM1=(3% $PHI:(((((2$STM2(1$STM3(0% J$2,I$2,C$2,SWITCH:$PHI0)1)
2)$OMEGA)$OMEGA)$VAL$C$2)$VAL$SWITCH)3).

$STM20=(11% $PHI,K,J,I,C,B,A,OUTPUT,INPUT:(10(9(8(7(6(5(4(3(2(1(
0READWRITE $TRUE0)C1)$PHI 2)K3)J4)I5)C6)B7)A8)OUTPUT9)INPUT10)11
).

$STM21=(8% $PHI,K,J,I,C,B,A,OUTPUT,INPUT:(7(6(5(4(3(2(1(0$PHI K0
)J1)52)C3)B4)A5)OUTPUT6)INPUT7)8).

$STM24=(8% $PHI,K,J,I,C,B,A,OUTPUT,INPUT:(7(6(5(4(3(2(1(0$PHI K0
)51)I2)C3)B4)A5)OUTPUT6)INPUT7)8).

$STM27=(13% $PHI,K,J,I,C,B,A,OUTPUT,INPUT:(12(11(10(9(8(2(1(0$PH
I K0)J1)I2)(7C(6(3(2$REPLACE (1(0$MINUS I0)41)2)63)(5(4C(3(2$RET
RIEVE (1(0$MINUS I0)41)2)63)4)(4(3(2$REPLACE (1(0$MINUS J0)41)2)
63)04)5)6)7)8)B9)A10)OUTPUT11)INPUT12)13).

$STM28=(8% $PHI,K,J,I,C,B,A,OUTPUT,INPUT:(7(6(5(4(3(2(1(0$PHI 50
)J1)I2)C3)B4)A5)OUTPUT6)INPUT7)8).

$STM31=(18% $PHI,K,J,I,C,B,A,OUTPUT,INPUT:(17(16(15(14(13(2(1(0$
PHI K0)J1)I2)(12C(11(3(2$REPLACE (1(0$MINUS I0)41)2)63)(10(4C(3(
2$RETRIEVE (1(0$MINUS I0)41)2)63)4)(9(3(2$REPLACE (1(0$MINUS J0)
41)2)63)(8(6$PLUS (5(4C(3(2$RETRIEVE (1(0$MINUS I0)41)2)63)4)(3(
2$RETRIEVE (1(0$MINUS J0)41)2)63)5)6)(7(6$MULT (5(4A(3(2$RETRIEV
E (1(0$MINUS I0)41)2)63)4)(3(2$RETRIEVE (1(0$MINUS K0)41)2)63)5)
6)(5(4B(3(2$RETRIEVE (1(0$MINUS K0)41)2)63)4)(3(2$RETRIEVE (1(0$
MINUS J0)41)2)63)5)7)8)9)10)11)12)13)B14)A15)OUTPUT16)INPUT17)18
).
```

```
$STM32=(10% $PHI,K,J,I,C,B,A,OUTPUT,INPUT:(9(8(7(6(5(4(3(2$PHI (
1(0$PLUS K0)11)2)J3)I4)C5)B6)A7)OUTPUT8)INPUT9)10).

$STM30=(2% $PHI:(1$STM31(0$STM32 $PHI0)1)2).

$STM29=(13% $PHI,K,J,I,C,B,A,OUTPUT,INPUT:(12(11(10(9(8(7(6(5(4(
3(2$IF (1(0$LE K0)101)2)(1$STM30(0$STM29 $PHI0)1)3)$PHI4)K5)J6)I
7)C8)B9)A10)OUTPUT11)INPUT12)13).

$STM33=(9% $PHI,K,J,I,C,B,A,OUTPUT,INPUT:(8(7(6(5(4(3(2(0$PHI K0
)(1(0$PLUS J0)11)2)I3)C4)B5)A6)OUTPUT7)INPUT8)9).

$STM26=(4% $PHI:(3$STM27(2$STM28(1$STM29(0$STM33 $PHI0)1)2)3)4).

$STM25=(13% $PHI,K,J,I,C,B,A,OUTPUT,INPUT:(12(11(10(9(8(7(6(5(4(
3(2$IF (1(0$LE J0)101)2)(1$STM26(0$STM25 $PHI0)1)3)$PHI4)K5)J6)I
7)C8)B9)A10)OUTPUT11)INPUT12)13).

$STM34=(8% $PHI,K,J,I,C,B,A,OUTPUT,INPUT:(7(6(5(4(3(2(1(0$PHI K0
)J1)(1(0$PLUS I0)11)2)C3)B4)A5)OUTPUT6)INPUT7)8).

$STM23=(3% $PHI:(2$STM24(1$STM25(0$STM34 $PHI0)1)2)3).

$STM22=(13% $PHI,K,J,I,C,B,A,OUTPUT,INPUT:(12(11(10(9(8(7(6(5(4(
3(2$IF (1(0$LE I0)101)2)(1$STM23(0$STM22 $PHI0)1)3)$PHI4)K5)J6)I
7)C8)B9)A10)OUTPUT11)INPUT12)13).

$STM35=(1(0READWRITE $FALSE0)C1).

$STM19=(5% $PHI:(((((((((4$STM20(3$STM21(2$STM22(1$STM35(0% K,J,
I,C,B,A,OUTPUT,INPUT:$PHI0)1)2)3)4)$OMEGA)$OMEGA)$OMEGA)(2(1(0$T
UPINIT 20)61)62))(2(1(0$TUPINIT 20)61)62))(2(1(0$TUPINIT 20)61)6
2))$OMEGA)$OMEGA)5).

$PROGRAM=(($STM19 $ID)$ID).
```

PART 2: THE COMPILER

2.1. Features and Organization

The compiler itself is written in standard PASCAL. It is a one pass translator, with the following well-distinguished execution phases:

-- lexical scanning by means of a finite state machine.

-- attributed LL(1) parsing for syntactic analysis and semantic activities , including type-checking procedures.

-- generation of lambda-expressions, employing a garbage collecting system for character strings of dynamic lengths.

Due to the size and sparseness of the transition tables of both the finite state automaton and the pushdown machine correspondiong to the LL(1) grammar (73 possible stack symbols and 50 input tokens), implicit program code was used to realize the automata.

The compiler generates a source program listing which includes: accumulated statement counts, accumulated semicolon counts, block levels, depths of nested loops, and of compound and case statements. The compiler can also produce a cross-reference of all identifiers with respect to the semicolon counts of their occurrences and a specification of their explicit types. Context-sensitive error messages are recorded on a temporary file which is finally appended to the source listings. Currently, three compiler options are supported which may be specified in the usual way within comment braces [5]: X±, S±, and U±. X- will supress the printing of the cross-reference, S+ will extend the syntax of the language accepted (see formal parameters and function declarations), and U+ will cause the compiler to attach superscripts to paired parenthesis in the code generated. The default values of these options are "(*$X+,S+,U-*)".

2.2. The Lexical Scanner

The lexical scanner advances through the input stream of characters until it recognizes a new token which it passes to the parser [7]. There are 50 different (parameterized) tokens which become the terminals of the later LL(1) grammar. Some have an associated parameter value. This value does not influence the parse but is used in later tasks. From a theoretical point of

view, each token and its parameter value are obtained by a single finite automaton, and the complete lexical scanner is just a parallel composition of these. The two most important automata are the identifier scanner and number scanner.

2.2.1. Identifiers

This compiler distinguishes PASCAL identifiers by their first ten characters, which are entered into a hashing table and eventually padded by blanks. The hashing function is the sum of the numerical codes of the first, second, fourth and fifth character modulo a prime number which is close to half of the size of the whole table. Hashing collisions are resolved by a chaining algorithm using the second half of the hashing table as overflow area. The parameter value of the token IDENTIFIER is the hashed table index of each recognized identifier. If there is no danger of ambiguities, identifiers and their corresponding hashing table indices are not distinguished any further.

Keywords cannot be used as identifiers. A binary search is conducted through an alphabetically sorted table of the 35 standard PASCAL keywords, and all but four (the operators AND, MOD, DIV, and IN) become tokens themselves.

2.2.2. Numbers

The compiler contains an explicit finite automaton to accept numbers [7]. In the following transition table each output symbol (denoted by a lower case letter) corresponds to a certain action specified below the table. The initial state is 1, and the final ("accepting") state 0:

STATE vs. INPUT CHARACTER

	'0'..'9'	'.'	'E'	'+', '-'	others
1	1 a	2 d	4 c	0 b	0 b
2	3 c	0 e	0 e	0 e	0 e
3	3 d	0 d	4 d	0 d	0 d
4	6 d	0 f	0 f	5 d	0 f
5	6 d	0 f	0 f	0 f	0 f
6	6 d	0 d	0 d	0 d	0 d

Actions:

a) Record a new digit in the integral part of number.

b) Unsigned integer terminated.
c) Unsigned real without fractional part encountered.
d) Process fractional and exponential part in unsigned real number.
e) If current character = ')' then unsigned integer terminated and current character := ']'.
If current character = '.' then unsigned integer terminated and current character := double dot.
Otherwise proceed like f).
f) Error in real constant: Digit expected but not found.

Two tokens, viz. UNSGINTEG and UNSGREAL, correspond to unsigned integers and real numbers, resp. . Their parameters contain their actual numerical value. Signs will be distinguished from "adding operators" on a later grammatical level.

There are six separate tokens for the various PASCAL operators. However, some may also serve another syntactic purpose. E.g. EQUALSYM in definitions of constants and types or PLUSMINUS in signed numbers.

Token:	Meaning of parameter values:
NOTSYM	None.
PLUSMINUS	1: '+', 2: '-'.
ORSYM	None.
MULTOPER	1: '*', 2: '/', 3: DIV, 4: MOD, 5: AND.
EQUALSYM	None.
RELOPER	2: '<>', 3: '<', 4: '>', 5: '<=', 6: '>=', 7: IN.

All literals are collected in a vector of characters, which is MAXSTRGL long. The token STRINGSYM associates the entry of a certain literal by its parameter field in the following fashion:

Parameter value = starting index * MAXSTRGL + length.

The remaining tokens correspond to special symbols without parameter values:

LPARASYM: '(', RPARASYM: ')', LBRACKSYM: '[', RBRACKSYM: ']',
SEMICSYM: ';', COMMASYM: ',', PERIODSYM: '.', DOUBLEDOT: '..',
COLONSYM: ':', BECOMES: ':=', POINTER: PASCAL pointer symbol.

Brackets may be also written as '(.' and '.)'. Comments are enclosed by braces or by '(*' and '*)'. The pointer symbol of this implemention is the ampersand.

2.3. An LL(1) Grammar for Standard PASCAL

Before proceeding with a compendious description of the attributed LL(1) translation, the underlying context-free grammar itself shall be scrutinized. It consists of 57 non-terminals, 50 terminals (namely all tokens described in section 2.2) and 135 productions. All but one non-terminnal yield disjoint selection sets [7] for different productions. The selection sets of the productions

(i) <else clause> ::= ELSESYM <statement>.
(ii) <else clause> ::= <empty>.

are {ELSESYM} for (i) and {ENDSYM, SEMICSYM, UNTILSYM, ELSESYM} for (ii). This is a consequence of the well-known ambiguity

if e1 then if e2 then S1 else S2.

By definition [5], each else clause is paired with the last unmatched then clause. This is equivalent to removing the ELSESYM from the selection set of (ii). With respect to this modification the grammar becomes LL(1) [7].+

Now the complete grammar shall be given in BNF notation. In addition, the selection set of each production will be specified unless its right-hand side starts with a terminal. (In this case, the terminal is the only element of its selection set.) The starting symbol is <program>:

(1) <identifierlist> ::= COMMASYM IDENTIFIER <identifierlist>.

(2) <identifierlist> ::= <empty>.
Selset(2) = {RPARASYM, SEMICSYM, COLONSYM}.

(3) <labeldclremainder> ::= COMMASYM UNSGINTEG <labeldclremainder>.

(4) <labeldclremainder> ::= SEMICSYM.

(5) <labeldeclaration> ::= LABELSYM UNSGINTEG <labeldclremainder>.

(6) <labeldeclaration> ::= <empty>.
Selset(6) = {CONSTSYM, TYPESYM, VARSYM, PROCSYM, FUNCSYM, BEGINSYM}.

(7) <nonidentconstrem> ::= IDENTIFIER.

+ It is not known to us whether there exists a "pure" LL(1) grammar for standard PASCAL. E.g. ALGOL 60 is known to be "inherently non-LL(1)" [6].

```
(8)  <nonidentconstrem> ::= UNSGINTEG.

(9)  <nonidentconstrem> ::= UNSGREAL.

(10) <nonidentconstant> ::= PLUSMINUS <nonidentconstrem>.

(11) <nonidentconstant> ::= UNSGINTEG.

(12) <nonidentconstant> ::= UNSGREAL.

(13) <nonidentconstant> ::= STRINGSYM.

(14) <constant> ::= IDENTIFIER.

(15) <constant> ::= <nonidentconstant>.
     Selset(15) = {UNSGINTEG, PLUSMINUS, UNSGREAL, STRINGSYM}.

(16) <constantlist> ::= COMMASYM <constant> <constantlist>.

(17) <constantlist> ::= <empty>.
     Selset(17) = {COLONSYM}.

(18) <constdefinpartrem> ::= IDENTIFIER EQUALSYM <constant>
                             SEMICSYM <constdefinpartrem>.

(19) <constdefinpartrem> ::= <empty>.
     Selset(19) = {TYPESYM, VARSYM, PROCSYM, FUNCSYM, BEGINSYM}.

(20) <constantdefinpart> ::= CONSTSYM IDENTIFIER EQUALSYM <cons-
                             tant> SEMICSYM <constdefinpartrem>.

(21) <constantdefinpart> ::= <empty>.
     Selset(21) = {TYPESYM, VARSYM, PROCSYM, FUNCSYM, BEGINSYM}.

(22) <simpletyperemaind> ::= DOUBLEDOT <constant>.

(23) <simpletyperemaind> ::= <empty>.
     Selset(23) = {RPARASYM, SEMICSYM, COMMASYM, RBRACKSYM,
                   ENDSYM}.

(24) <simpletype> ::= LPARASYM IDENTIFIER <identifierlist>
                      RPARASYM.

(25) <simpletype> ::= IDENTIFIER <simpletyperemaind>.

(26) <simpletype> ::= <nonidentconstant> DOUBLEDOT <constant>.
     Selset(26) = {UNSGINTEG, PLUSMINUS, UNSGREAL, STRINGSYM}.

(27) <simpletypelist> ::= COMMASYM <simpletype> <simpletype-
                          list>.
```

```
(28) <simpletypelist> ::= <empty>.
     Selset(28) = {RBRACKSYM}.

(29) <variant> ::= <constant> <constantlist> COLONSYM LPARASYM
                   <fieldlist> RPARASYM.
     Selset(29) = {IDENTIFIER, UNSGINTEG, PLUSMINUS, UNSGREAL,
                   STRINGSYM}.

(30) <variant> ::= <empty>.
     Selset(30) = {RPARASYM, SEMICSYM, ENDSYM}.

(31) <variantlist> ::= SEMICSYM <variant> <variantlist>.

(32) <variantlist> ::= <empty>.
     Selset(32) = {RPARASYM, ENDSYM}.

(33) <tagfieldremainder> ::= COLONSYM IDENTIFIER.

(34) <tagfieldremainder> ::= <empty>.
     Selset(34) = {OFSYM}.

(35) <fieldlistremaind> ::= SEMICSYM <fieldlist>.

(36) <fieldlistremaind> ::= <empty>.
     Selset(36) = {RPAASYM, ENDSYM}.

(37) <recordsection> ::= IDENTIFIER <identifierlist> COLONSYM
                         <type>.

(38) <recordsection> ::= <empty>.
     Selset(38) = {RPARASYM, SEMICSYM, ENDSYM}.

(39) <fieldlist> ::= <recordsection> <fieldlistremaind>.
     Selset(39) = {IDENTIFIER, RPARASYM, SEMICSYM, ENDSYM}.

(40) <fieldlist> ::= CASESYM IDENTIFIER <tagfieldremainder> OF-
                     SYM <variant> <variantlist>.

(41) <unpackstructtype> ::= ARRAYSYM LBRACKSYM <simpletype>
                            <simpletypelist> RBRACKSYM OFSYM
                            <type>.

(42) <unpackstructtype> ::= RECORDSYM <fieldlist> ENDSYM.

(43) <unpackstructtype> ::= FILESYM OFSYM <type>.

(44) <unpackstructtype> ::= SETSYM OFSYM <simpletype>.
```

```
(45) <type> ::= <simpletype>.
     Selset(45) = {IDENTIFIER, LPARASYM, UNSGINTEG, PLUSMINUS,
                   UNSGREAL, STRINGSYM}.

(46) <type> ::= PACKEDSYM <unpackstructtype>.

(47) <type> ::= <unpackstructtype>.
     Selset(47) = {ARRAYSYM, RECORDSYM, FILESYM, SETSYM}.

(48) <type> ::= POINTER IDENTIFIER.

(49) <typedefinpartrem> ::= IDENTIFIER EQUALSYM <type> SEMICSYM
                            <typedefinpartrem>.

(50) <typedefinpartrem> ::= <empty>.
     Selset(50) = {VARSYM, PROCSYM, FUNCSYM, BEGINSYM}.

(51) <typedefinitionprt> ::= TYPESYM IDENTIFIER EQUALSYM <type>
                             SEMICSYM <typedefinpartrem>.

(52) <typedefinitionprt> ::= <empty>.
     Selset(52) = {VARSYM, PROCSYM, FUNCSYM, BEGINSYM}.

(53) <variabledclprtrem> ::= IDENTIFIER <identifierlist> COLON-
                             SYM <type> SEMICSYM <variabledcl-
                             prtrem>.

(54) <variabledclprtrem> ::= <empty>.
     Selset(54) = {PROCSYM, FUNCSYM, BEGINSYM}.

(55) <variabledeclarprt> ::= VARSYM IDENTIFIER <identifierlist>
                             COLONSYM <type> SEMICSYM <variable-
                             dclprtrem>.

(56) <variabledeclarprt> ::= <empty>.
     Selset(56) = {PROCSYM, FUNCSYM, BEGINSYM}.

(57) <formalparameter> ::= IDENTIFIER <identifierlist> COLONSYM
                           IDENTIFIER.

(58) <formalparameter> ::= VARSYM IDENTIFIER <identifierlist>
                           COLONSYM IDENTIFIER.
```

If the compiler option S+ is activated, an explicit <type> will be accepted in formal parameters (productions 57 and 58). Any implicitely defined scalar identifiers within this <type> are then global to the scope of the procedure or function body. No pointer references are forwarded.

(59) <formalparameter> ::= FUNCSYM IDENTIFIER <identifierlist> COLONSYM IDENTIFIER.

(60) <formalparameter> ::= PROCSYM IDENTIFIER <identifierlist>.

(61) <formparameterlist> ::= SEMICSYM <formalparameter> <formparameterlist>.

(62) <formparameterlist> ::= <empty>.
Selset(62) = {RPARASYM}.

(63) <formparameterpart> ::= LPARASYM <formalparameter> <formparameterlist> RPARASYM.

(64) <formparameterpart> ::= <empty>.
Selset(64) = {SEMICSYM, COLONSYM}.

(65) <procfuncdeclarat> ::= PROCSYM IDENTIFIER <formparameterpart> SEMICSYM <block>.

(66) <procfuncdeclarat> ::= FUNCSYM IDENTIFIER <formparameterpart> COLONSYM IDENTIFIER SEMICSYM <block>.

If the compiler option S+ is activated, an explicit <type> will be accepted in the function return type. Any implicitely defined scalar identifiers within this <type> are then global to the scope of the function body. No pointer references are forwarded.

(67) <procfuncdclpart> ::= <procfuncdeclarat> SEMICSYM <procfuncdclpart>.
Selset(67) = {PROCSYM, FUNCSYM}.

(68) <procfuncdclpart> ::= <empty>.
Selset(68) = {BEGINSYM}.

(69) <expressionlist> ::= COMMASYM <expression>.

(70) <expressionlist> ::= <empty>.
Selset(70) = {RPARASYM, RBRACKSYM}.

(71) <variableselector> ::= LBRACKSYM <expression> <expressionlist> RBRACKSYM <variableselector>.

(72) <variableselector> ::= PERIODSYM IDENTIFIER <variableselector>.

(73) <variableselector> ::= POINTER <variableselector>.

```
(74) <variableselector> ::= <empty>.
     Selset(74) = {RPARASYM, SEMICSYM, COMMASYM, EQUALSYM,
                   RBRACKSYM, DOUBLEDOT, BECOMES, DOSYM, OFSYM,
                   ORSYM, TOSYM, ENDSYM, ELSESYM, THENSYM,
                   UNTILSYM, DOWNTOSYM, PLUSMINUS, RELOPER,
                   MULTOPER}.

(75) <actparameterpart> ::= LPARASYM <expression> <expression-
                            list> RPARASYM.

(76) <identifierremaind> ::= <variableselector>.
     Selset(76) ={PERIODSYM, RPARASYM, SEMICSYM, COMMASYM,
                  EQUALSYM, LBRACKSYM, RBRACKSYM, DOUBLEDOT, DO-
                  SYM, OFSYM, ORSYM, TOSYM, ENDSYM, ELSESYM,
                  THENSYM, UNTILSYM, DOWNTOSYM, POINTER, PLUS-
                  MINUS, RELOPER, MULTOPER}.

(77) <identifierremaind> ::= <actparameterpart>.
     Selset(77) = {LPARASYM}.

(78) <setelementremaind> ::= DOUBLEDOT <expression>.

(79) <setelementremaind> ::= <empty>.
     Selset(79) = {COMMASYM, RBRACKSYM}.

(80) <setelement> ::= <expression> <setelementremaind>.
     Selset(80) = {LPARASYM, NOTSYM, STRINGSYM, PLUSMINUS,
                   IDENTIFIER, UNSGINTEG}.

(81) <setelementlist> ::= COMMASYM <setelement> <setelement-
                          list>.

(82) <setelementlist> ::= <empty>.
     Selset(82) = {RBRACKSYM}.

(83) <setrange> ::= <setelement> <setelementlist>.
     Selset(83) = {LPARASYM, NOTSYM, STRINGSYM, PLUSMINUS,
                   IDENTIFIER, UNSGINTEG}.

(84) <setrange> ::= <empty>.
     Selset(84) = {RBRACKSYM}.

(85) <factor> ::= NOTSYM <factor>.

(86) <factor> ::= IDENTIFIER <identifieremaind>.

(87) <factor> ::= STRINGSYM.

(88) <factor> ::= UNSGINTEG.

(89) <factor> ::= UNSGREAL.
```

```
(90) <factor> ::= NILSYM.

(91) <factor> ::= LBRACKSYM <setrange> RBRACKSYM.

(92) <factor> ::= LPARASYM <expression> RPARASYM.

(93) <factorlist> ::= MULTOPER <factor> <factorlist>.

(94) <factorlist> ::= <empty>.
     Selset(94) = {RPARASYM, SEMICSYM, COMMASYM, EQUALSYM,
                   RBRACKSYM, DOUBLEDOT, DOSYM, OFSYM, ORSYM,
                   TOSYM, ENDSYM, ELSESYM, THENSYM, UNTILSYM,
                   DOWNTOSYM, PLUSMINUS, RELOPER}.

(95) <term> ::= <factor> <factorlist>.
     Selset(95) = {LPARASYM, LBRACKSYM, NILSYM, NOTSYM, STRING-
                   SYM, IDENTIFIER, UNSGREAL, UNSGINTEG}.

(96) <termlist> ::= PLUSMINUS <term> <termlist>.

(97) <termlist> ::= ORSYM <term> <termlist>.

(98) <termlist> ::= <empty>.
     Selset(98) = {RPARASYM, SEMICSYM, COMMASYM, EQUALSYM,
                   RBRACKSYM, DOUBLEDOT, DOSYM, OFSYM, TOSYM,
                   ENDSYM, ELSESYM, THENSYM, UNTILSYM, DOWNTO-
                   SYM, RELOPER}.

(99) <simpleexpression> ::= PLUSMINUS <term>.

(100) <simpleexpression> ::= <term> <termlist>.
      Selset(100) = {LPARASYM, LBRACKSYM, NILSYM, NOTSYM,
                     STRINGSYM, IDENTIFIER, UNSGREAL, UNSG-
                     INTEG}.

(101) <simpleexpressrem> ::= EQUALSYM <simpleexpression>.

(102) <simpleexpressrem> ::= RELOPER <simpleexpression>.

(103) <simpleexpressrem> ::= <empty>.
      Selset(103) = {RPARASYM, SEMICSYM, COMMASYM, RBRACKSYM,
                     DOUBLEDOT, DOSYM, OFSYM, TOSYM, ENDSYM,
                     ELSESYM, THENSYM, UNTILSYM, DOWNTOSYM}.

(104) <expression> ::= <simpleexpression> <simpleexpressrem>.
      Selset(104) = {LPARASYM, LBRACKSYM, NILSYM, NOTSYM,
                     STRINGSYM, PLUSMINUS, IDENTIFIER, UNSGREAL,
                     UNSGINTEG}.
```

(105) <simplestatemntrem> ::= <variableselector> BECOMES <expression>.
Selset(105) = {PERIODSYM, LBRACKSYM, POINTER, BECOMES}.

(106) <simplestatemntrem> ::= <actparameterpart>.
Selset(106) = {LPARASYM}.

(107) <simplestatemntrem> ::= <empty>.
Selset(107) = {SEMICSYM, ENDSYM, UNTILSYM, ELSESYM}.

(108) <compoundstmntrem> ::= SEMICSYM <statement> <compoundstmntrem>.

(109) <compoundstmntrem> ::= ENDSYM.

(110) <elseclause> ::= ELSESYM <statement>.

(111) <elseclause> ::= <empty>.
Selset(111) = {SEMICSYM, ENDSYM, UNTILSYM}.

(112) <caseelement> ::= <constant> <constantlist> COLONSYM <statement>.
Selset(112) = {IDENTIFIER, UNSGINTEG, PLUSMINUS, UNSGREAL, STRINGSYM}.

(113) <caseelement> ::= <empty>.
Selset(113) = {SEMICSYM, ENDSYM}.

(114) <caseelementlist> ::= SEMICSYM <caseelement> <caseelementlist>.

(115) <caseelementlist> ::= ENDSYM.

(116) <repeatstatemntlst> ::= SEMICSYM <statement> <repeatstmntlist>.

(117) <repeatstatemntlst> ::= UNTIL.

(118) <forstatementrem> ::= TOSYM <expression> DOSYM <statement>.

(119) <forstatementrem> ::= DOWNTOSYM <expression> DOSYM <statement>.

(120) <withvariablelist> ::= COMMASYM IDENTIFIER <variableselector> <withvariablelist>.

(121) <withvariablelist> ::= DOSYM.

(122) <unlabeledstatemnt> ::= IDENTIFIER <simplestatemntrem>.

(123) <unlabeledstatemnt> ::= BEGINSYM <statement> <compound-stmntrem>.

(124) <unlabeledstatemnt> ::= IFSYM <expression> THENSYM <statement> <elseclause>.

(125) <unlabeledstatemnt> ::= CASESYM <expression> OFSYM <caseelement> <caseelementlist>.

(126) <unlabeledstatemnt> ::= WHILESYM <expression> DOSYM <statement>

(127) <unlabeledstatemnt> ::= REPEATSYM <statement> <repeatstatemntlst> <expression>.

(128) <unlabeledstatemnt> ::= FORSYM IDENTIFIER BECOMES <expression> <forstatementrem>.

(129) <unlabeledstatemnt> ::= WITHSYM IDENTIFIER <variableselector> <withvariablelist> <statement>.

(130) <unlabeledstatemnt> ::= GOTOSYM UNSGINTEG.

(131) <unlabeledstatemnt> ::= <empty>.
Selset(131) = {SEMICSYM, ENDSYM, ELSESYM, UNTILSYM}.

(132) <statement> ::= UNSGINTEG COLONSYM <unlabeledstatemnt>.

(133) <statement> ::= <unlabeledstatemnt>.
Selset(133) = {IDENTIFIER, SEMICSYM, ENDSYM, CASESYM, BEGINSYM, IFSYM, WHILESYM, REPEATSYM, FORSYM, WITHSYM, GOTOSYM, ELSESYM, UNTILSYM}.

(134) <block> ::= <labeldeclaration> <constdefinpart> <typedefinitionprt> <variabledeclarprt> <procfuncdeclarat> BEGINSYM <statement> <compoundstmntrem>.
Selset(134) = {LABELSYM, CONSTSYM, TYPESYM, VARSYM, PROCSYM, FUNCSYM, BEGINSYM}.

(135) <program> ::= PROGRAMSYM IDENTIFIER LPARASYM IDENTIFIER <identifierlist> RPARASYM SEMICSYM <block> PERIODSYM.

The transition table of the corresponding one-state pushdown automaton is about 33 print pages long. This table has been produced by a program which inspects given context-free grammars for being LL(1).

2.4. An Attributed Translation of Lists

The syntax of PASCAL is rich in lists of certain entities (e.g. identifier list, constant list, simple type list, expression list, simple type list, formal parameter list, variant list, etc.). One general scheme applies throughout the tranlation: Let us assume first that the non-terminals <entity>, <list> and <item> have the following synthesized and inherited attributes [7]:

DESCR..... a data structure containing the description of any item (synth.).
FIRST, SEC... same as DESCR (inher.).
HEAD..... The head pointer to a list of all item DESCRs (synth.).
CAR, CDR..... pointers to lists of item DESCRs (synth.).

A suitable translation grammar [7] to build a list of item descriptors follows. Action symbols will be surrounded by dashes:

(i) <entity>(HEAD) ::= <item>(FIRST) <list>(FIRST,HEAD).
(ii) <list>(FIRST,CAR) ::= <separator> <item>(SEC)
<list>(SEC,CDR) -action-.
(iii) <list>(FIRST,CAR) ::= <terminator> -CDR:=nil- -action-.

Where -action- means:

-allocate CAR and put FIRST into it; catenate CDR to it-.

This particular grammar yields a simple method for recovering from a syntactic error: Suppose <list> is called but neither a <separator> nor a <terminator> appear as input tokens. Then CAR can be set to nil and the error handler may advance the input stream to a global synchronization symbol such as a SEMICSYM (see also section 2.8).

2.5. The Main Data Structures Needed in Translation

Each block of the source program may introduce a new set of identifiers which must be disregarded when the parsing of this block is completed. A record describing each new identifier will contain the block level number of this identifier. It is pushed onto a stack of identifier descriptors as soon as the referred identifier is sufficiently defined. On leaving a block, all identifier descriptors of its level are popped off this stack. In order to find an identifier descriptor within this stack, its position is entered into the identifier's hashing table element. Should there already be an address of an identifier defined at a lower block level, a stacking mechanism is invoked. It should be noticed that this algorithm reduces the search time for an identifier to a look-up in the hashing table. Predefined ident-

ifiers are pushed onto this stack at the very beginning of the parse and possess the level number zero.

Six classes of identifiers are distinguished. Identifiers may denote scalars, types, variables, record fields, procedures, or functions. An identifier description record contains the following fields (some will be pointers to a record describing a certain type which will be discussed below):

IDNR..... the hashing index of the referenced identifier.
LEVNR..... the block level of its definition.
IDCLASS... the class it belongs to.

Depending on the value of the field IDCLASS, the descriptor recordcontains the following additional fields:

For a scalar identifier:
   STYP.... a pointer to its (scalar) type descriptor.
   VALUE... its cardinality.

For a type identifier:
   TYP... a pointer to the type it denotes.

For a variable:
   TYP.... a pointer to its type descriptor.
   PARM... a flag signalling whether it is a formal parameter and if so what kind of parameter it is (variable or value).

For a record field:
   TYP... a pointer to its type record.

For a procedure or function:
   ARGTYPS.... a list of type records for its parameters.
   SWFORW..... a flag signalling whether forward declared.
   FORWARGS... a list of identifier descriptors for all formal parameters in case of forward declaration. These records will be pushed onto the stack as soon as the procedure or function body is specified.
   RETTYP..... the function's return type.
   PARM..... a flag similar to the PARM field in a variable.

There are five types, namely scalar, array, record and pointer types, and the undefined type.[+] Each type record contains a switch telling which class the type belongs to and the following corresponding fields:

[+] The compiler does not yet support set and file types. They are treated as undefined types.

For a scalar type:
SCIDNR..... its type identifier's hashing index.
SCLEVNR..... the level of its definition.
LOWBND, HIGBND... its range of cardinalities.
No distinction is made between subrange types and their matching scalar types (encompassing the full range). The type INTEGER at level zero ranges over -MAXINT .. MAXINT. The type REAL at level zero has no associated bounds. If no explicit type identifier is given, a unique identifier "$IMPLTn" (where n is a certain number) will be used instead. The compiler internally translates a label N into a scalar identifier '$LABELN' and gives it the scalar type 'LABEL' of level zero ranging from 1 to 9999.

For an array type:
INDXTYP... the (scalar) type record of the array index.
COMPTYP... the type record of the array component.
SWPACK.... a flag signalling whether the array is packed.
Matrices and multidimensional arrays will always obtain an array type as their component types. E.g. array [it1, it2] of t will become array [it1] of array [it2] of t.

For a record type:
SECTNS... a list of field identifier descriptors.
SWPACK... a flag signalling whether the record is packed.

For a pointer type:
PTRIDNR.... referenced type identifier.
REFERTYP... referenced type record.
This compiler treats all pointer type references as forward defined. A list of all unresolved pointer type records is kept until all type definitions are parsed. Then the appropriate type record pointers corresponding to PTRIDNR are assigned to REFERTYP.+

For of the undefined type class:
UNDFIDNR... the undefined type identifier (if known).
From a theoretical point of view all compiler routines taking type descriptors as arguments (e.g. the type checking facilities) are partial functions in the sense that a single argument of the undefined type forces all results to be of this type also.

In order to reduce the number of attributes attached to symbols of the grammar involving the parsing of expressions, a global stack is constructed to serve the following purpose: Each

---

+ We believe that this is a natural resolution of the following ambiguity in PASCAL: Given type R = record F:...; G: @R end, then G should refer to R itself rather than a different type R defined on a lower block level.

stack element contains a flag which is set to false unless the expression currently derived is a single variable. Immediatly after the parse of an expression is completed the top element of this stack may be saved for later inspection. Thus non-variable arguments are discovered in place of variable parameters. The compiler actually uses a doubly linked list in order to re-use popped off stack elements.

2.6. Strings of Fluid Length

This compiler utilizes a garbage collection system for character strings of fluid lengths. By this we mean that whenever during manipulation a string would become longer than the space reserved for it, it is re-allocated and its old position released for garbage collection.

The compiler builds the object code by a recursive process very similar to the representation rules of part one. Thus the final length of a string of lambda-calculus code can by no means be estimated beforehand. The string management subsystem is considered to be an essential tool for successful code generation. It resides completely independently of the compilation routines, and it can be used whenever it is required to work with strings whose lengths cannot be determined prior to their actual use.

The contents of all strings in use are put into a common area of core -- for instance a very long string itself. Then every string may be referred to by a record containing its starting address in the string workspace, its current length, the space currently reserved for it, and a marker signalling whether it is in use or free to be re-used. The system provides procedures for allocating new strings, assigning literals and other strings to strings, concatenating strings and releasing occupied string space. All string description records are linked together in a list for garbage collection purposes. As soon as a string is to be allocated but no more workspace is available, three passes of garbage collection and storage compaction are attempted to recover space for this request: first the list of string descriptors is searched for a string large enough to satisfy the request. If this does not succeed, then as many unused strings as necessary are removed from the list and the workspace is properly compacted. Finally a necessary amount of strings may have their allocated lengths reduced to their current lengths.

2.7. Summary of Attributes

Any symbol of a translation grammar may have one or several attributes associated with it [7]. The following briefly describes the meaning of these attributes with respect to the grammatical symbols, and whether they are inherited or syn-

thesized:

<identifierlist>(FIRSTID, CARIDLST):
   FIRSTID..... identifier index (inher.).
   CARIDLST.... list of identifiers (synth.).

<nonidentconstrem>(SIGN, CONSTYP, CONSVAL):
   SIGN........ sign of non identifier constant (inher.).
   CONSTYP..... pointer to its type record (synth.).
   CONSVAL..... its explicit value (synth.).

<nonidentconstant>(CONSTYP, CONSVAL):
   Same as for <nonidentconstrem> (both synth.).

<constant>(CONSTYP, CONSVAL):
   Same as for <nonidentconstrem> (both synth.).

<constantlist>(FIRSTTYP, FIRSTVAL, CARCONSLST, MATCHTYP):
   FIRSTTYP.... pointer to type record (inher.).
   FIRSTVAL.... explicit value of constant (inher.).
   CARCONSLST.. list of explicit values of constants (synth.).
   MATCHTYP.... pointer to a (scalar) type record which must
                match to all constant types incl. FIRSTTYP
                (inher.).

<simpletyperemaind>(FIRSTID, RETTYP, REFID):
   FIRSTID..... identifier which begins <type> (inher.).
   RETTYP...... pointer to completed type record (synth.).
   REFID....... index of type identifier which is to be defined
                (if explicit type definition, otherwise zero);
                necessary for scalar types. (inher.).

<simpletype>(RETTYP, REFID):
   Same as for <simpletyperemaind>.

<simpletypelist>(FIRSTTYP, CARSMPLST, SWPACK)
   FIRSTTYP.... pointer to type record (inher.).
   CARSMPLST... list of (scalar) type records (synth.).
   SWPACK...... flag whether corresponding array is packed or
                not (inher.).

<variant>(RECLST, MATCHTYP):
   RECLST...... list of field identifier descriptors (synth.).
   MATCHTYP.... type record of preceeding tag field (inher.).

<variantlist>(FIRSTVAR, CARRECLST, MATCHTYP):
   FIRSTVAR.... list of field identifier descriptors (inher.).
   CARRECLST... list of field identifier descriptors (synth.).
   MATCHTYP.... type record of preceeding tag field (inher.).

<tagfieldremainder>(FIRSTID, REC, MATCHTYP):
FIRSTID..... identifier which begins tag field (inher.).
REC..... tag field identifier descriptor (if any otherwise nil) (synth.).
MATCHTYP.... pointer to type record of tag field (synth.).

<fieldlistremaind>(RECLST):
RECLST..... list of field identifier descriptors (if any otherwise nil) (synth.).

<recordsection>(RECLST):
Same as for <fieldlistremaind>.

<fieldlist>(FLDLST):
FLDLST..... list of field identifier descriptors (synth.).

<unpackstructtype>(RETTYP, SWPACK, REFID):
RETTYP..... pointer to complete type record (synth.).
SWPACK..... flag whether type is packed or not (inher.).
REFID..... same as REFID in <simpletypremaind> (inher.).

<type>(RETTYP, REFID):
Same as in <unpackstructype>.

<formalparameter>(RETARG, RETACT):
RETARG..... type record pointer list of parameters as required in the ARGTYPS field of a procedure or function identifier description. (synth.).
RETACT..... list of parameter desriptions (synth.).

<formparameterlist>(FIRSTARG, FIRSTACT, CARARGLST, CARACTLST):
FIRSTARG.... list of type record pointers (inher.).
FIRSTACT.... list of identifier record pointers (inher.).
CARARGLST... list of parameter types (synth.).
CARACTLST... list of parameter descriptions (synth.).

<formparameterpart>(ARGLST, ACTLST):
ARGLST..... list of all parameter types (if any otherwise nil) (synth.).
ACTLST..... list of all parameter descriptions (if any otherwise nil) (synth.).

<expressionlist>(FIRSTCOD, FIRSTTYP, FIRSTSWVAR, CAREXPLST):
FIRSTCOD.... string pointer (see section 2.6) (inher.).
FIRSTTYP.... type record pointer (inher.).
FIRSTSWVAR.. flag whether expression is a variable or not; necessary to determine if an argument is a variable (inher.).
CAREXPLST... list of expression constituents which consist of their type records, string pointers to their code and "variable flags" like FIRSTSWVAR above (synth.).

```
<variableselector>(SWASSIGN, REPLLST, CODIN, TYPIN,
                   CODOUT, TYPOUT):
   SWASSIGN.... flag  signalling  if called at left hand side of
                assignment (inher.).
   REPLLST..... list of subscripts and array bounds in case
                SWASSIGN is true; needed to compile according to
                the last representation rule of section 1.7
                (inher. and synth.).
   CODIN....... string pointer to current code (inher.).
   TYPIN....... type record pointer of current type (inher.).
   CODOUT...... string pointer to new code (synth.).
   TYPOUT...... type record pointer of new type (synth.).

<actparameterpart>(ACTEXPLST):
   ACTEXPLST... same as CAREXPLST in <expressionlist>.

<identifierremaind>(ID, CODOUT, TYPOUT):
   ID.......... identifier in front of it (inher.).
   CODOUT, TYPOUT.. same as in <variableselectors>.

<factor>(FACCOD, FACTYP):
   FACCOD...... string pointer to code of factor (synth.).
   FACTYP...... type record pointer of its type (synth.).

<factorlist>(PRIORCOD, PRIORTYP, RETCOD, RETTYP):
   PRIORCOD.... string pointer (inher.).
   PRIORTYP.... type record pointer (inher.).
   RETCOD...... string  pointer  to  complete  code  of  factors
                (synth.).
   RETTYP...... type  record  pointer  of  their  resulting type
                (synth.).

<term>(TERMCOD, TERMTYP):
   Similar to attributes of <factor>.

<termlist>(PRIORCOD, PRIORTYP, RETCOD, RETTYP):
   Similar to attributes of <factorlist>.

<simpleexpression>(SEXPCOD, SEXPTYP):
   Similar to attributes of <factor>.

<simpleexpressrem>(PRIORCOD, PRIORTYP, RETCOD, RETTYP):
   Similar to attributes of <factorlist>.

<expression>(EXPCOD, EXPTYP):
   EXPCOD...... string pointer to expression code (synth.).
   EXPTYP...... pointer to its type record (synth.).

<simplestatemntrem>(ID):
   ID.......... identifier in front of it (inher.).
```

<compoundstmntrem>(FIRSTSTMNR, COMPSTMCOD):
FIRSTSTMNR.. statement number (inher.).
COMPSTMCOD.. string pointer to code of compound statement (see also section 1.6) (inher. and synth.).

<elseclause>(ELSESTMNR):
ELSESTMNR... statement number (inher.).

<caseelement>(CONSLST, MATCHTYP):
CONSLST..... list of explicit values of case labels (synth.).
MATCHTYP.... pointer to a (scalar) type record which must match all case label types (inher.).

<caseelementlist>(FIRSTCONSLST, CARCONSLST, MATCHTYP):
FIRSTCONSLST.. list of expl. values of case labels (inher.).
CARCONSLST.. list of expl. values of all case labels(synth.).
MATCHTYP.... same as in <caseelement>.

<forstatementrem>(CONTRTYP):
CONTRTYP.... type rec. pointer of control variable (inher.).

Each terminal (viz. each token) has only one (synthesized) attribute: its parameter value, if any was assigned.

2.8. Error Diagnostics and Error Recovery

The error diagnostic routines take advantage of the LL(1) property of the underlying grammar. Illegal tokens are discovered as soon as they are obtained [7] namely if they are not contained in the selection set of a non-terminal which is to be derived. A typical error message is thus

"VARIABLESELECTOR STARTS WITH IDENTIFIER"

or if terminals do not match

"; EXPECTED, BUT : FOUND"

All other error messages are adjusted to standard PASCAL [5] though their text usually includes some specific information such as an incorrectly used identifier. The error messages are enumerated according to [5].

The error recovery is probably the most complicated process of this compiler. Some general guidelines are explained now, but for more details the reader is referred to the compiler source. The lexical scanner treats illegal characters like blank spaces. On encountering a bad token, the parser proceeds until it finds a synchronizing symbol (SEMICSYM, ENDSYM, ELSESYM, UNTILSYM). Then it ignores all symbols of the current derivation ("pops the stack") until continuation by the synchronizing token is

possible. Some tokens should not be passed during the synchronization (PROCSYM, FUNCSYM, RECORDSYM, BEGINSYM, CASESYM, REPEATSYM), because the essential program structure would be lost. In such cases the compilation is halted. Semantic errors are repaired quite thoroughly. A separate undefined type was introduced for this purpose (see also UNDFIDNR in section 2.5). However, in some cases the type might be constructed from the context.

2.9. Example#5

The following sample program contains many errors which the compiler detected and reported:

```
 STMNR LEV NST SEMIC   SOURCE CODE:

    0   0   0     1    PROGRAM ERRONEOUS(INPUT);
    0   1   0     1    (* This program tests error diagnostics
    0   1   0     1       and error recovery *)
    0   1   0     2     LABEL 1, 2, 1;
    0   1   0     4     CONST C1='A'; C2='YZ';
    0   1   0     6     TYPE SR1=C1..'Z'; SR2=-5..0;
    0   1   0     7      PTR=@REC2;
    0   1   1     8      REC1=RECORD RF1, RF2: CHAR;
    0   1   1     8            CASE PTR OF
    0   1   1     9              'B': (RF3: @REC1);
    0   1   1     9              'Z': (RF1: INTEGER)
    0   1   1    10            END;
    0   1   0    12     VAR V1: BOOLEAN; V2: @REC1;
    0   1   0    13      V3: (TRUE, FALSE);
    0   1   0    13      V4: PACKED ARRAY (.SR1, (ONE, TWO).) OF
    0   1   1    14          RECORD VF1: ONE..TWO;
    0   1   2    16           VF2: RECORD VF3: @REC1; END;
    0   1   1    17          END;
    0   1   0    18      C2: INTEGER;
    0   1   0    20     PROCEDURE P(A: SR2); FORWARD;
    0   1   0    20     (*$S+ allow extented syntax *)
    0   2   0    21     FUNCTION F(VAR P1, P2: BOOLEAN): 1..100;
    0   1   0    22      FORWARD; (*$S- inhibit extensions *)
    0   2   0    23     PROCEDURE P(A: SR2);
    2   2   1    24      BEGIN NEW(V2, 'B');
    3   2   1    24       3: IF TRUE
    4   2   1    25           THEN V4(.C2, ONE.).VF2.VF5:=V2;
    5   2   1    26       P( F(NOT V1, V1) );
    6   2   1    27      END;
    8   1   1    28     BEGIN PUT;
    9   1   1    28      FOR V4:=3 DOWNTO -5 DO
   10   1   2    28       CASE V2@.RF1 OF
   11   1   2    29         'A', 'B': PP(-23);
   12   1   2    30         'C': GOTO 4;
   13   1   2    32         'D', 'A':;;
   14   2   2    32         'E': WITH V4(.'C', THREE.), VF2 DO
```

```
  15   3   2    33              VF3@.RF3@.RF1 := SR2;
  15   1   2    34          END;
  16   1   1    35        IF F(V1)<>5 AND C1='''' THEN I:=I+1;
  17   1   1    36        X:=5.E-7;
  18   1   1    36      END.

REF IDENTIFIER CLASS, TYPE, REFERENCES:     ***ERRONEOUS***

   1  $LABEL1    SCALAR, LABEL 0 .. 9999 (ORDERS ONLY) 2,
   1  $LABEL2    SCALAR, LABEL 0 .. 9999 (ORDERS ONLY)
  24  $LABEL3    SCALAR, *** UNDEFINED ***
  29  $LABEL4    SCALAR, *** UNDEFINED ***
  18  A          VARIABLE, INTEGER -5 .. 0 (ORDERS ONLY)
  10  BOOLEAN    TYPE, BOOLEAN 0 .. 1 (ORDERS ONLY) 20,
   7  CHAR       TYPE, CHAR 0 .. 255 (ORDERS ONLY)
   2  C1         SCALAR, CHAR 0 .. 255 (ORDERS ONLY) 4, 34,
   3  C2         SCALAR, PACKED ARRAY (. INTEGER 1 .. 2 (ORDERS ON
                 LY) .) OF CHAR 0 .. 255 (ORDERS ONLY) 18, 24,
  20  F          ENTRY( VAR, BOOLEAN 0 .. 1 (ORDERS ONLY) ; VAR, B
                 OOLEAN 0 .. 1 (ORDERS ONLY) ; ) : INTEGER 1 .. 10
                 0 (ORDERS ONLY) *** UNRESOLVED FORWARD REFERENCE
                 *** 25, 34,
  12  FALSE      SCALAR, $IMPLT1 0 .. 1 (ORDERS ONLY)
   0  INPUT      VARIABLE, @INTEGER
   9  INTEGER    TYPE, INTEGER -2147483647 .. 2147483647 (ORDERS O
                 NLY) 17,
  13  ONE        SCALAR, $IMPLT2 0 .. 1 (ORDERS ONLY) 13, 24,
  27  OUTPUT     VARIABLE, *** UNDEFINED ***
  18  P          ENTRY( INTEGER -5 .. 0 (ORDERS ONLY) ; ) 23, 25,
  28  PP         ENTRY( INTEGER -2147483647 .. 2147483647 (ORDERS
                 ONLY) ; )
   6  PTR        TYPE, @REC2 8,
   7  REC1       TYPE, RECORD RF2 :, RF1 :, RF3 :, RF1 :, 8, 11, 1
                 4,
   6  REC2       TYPE, REC2 , *** UNDEFINED ***
   8  RF1        RECORD FIELD, CHAR 0 .. 255 (ORDERS ONLY) 28, 32,
   9  RF1        RECORD FIELD, INTEGER -2147483647 .. 2147483647 (
                 ORDERS ONLY)
   8  RF2        RECORD FIELD, CHAR 0 .. 255 (ORDERS ONLY)
   8  RF3        RECORD FIELD, @REC1 32,
   4  SR1        TYPE, CHAR 193 .. 233 (ORDERS ONLY) 13,
   5  SR2        TYPE, INTEGER -5 .. 0 (ORDERS ONLY) 18, 22, 32,
  32  THREE      VARIABLE, *** UNDEFINED ***
  12  TRUE       SCALAR, $IMPLT1 0 .. 1 (ORDERS ONLY) 24,
  13  TWO        SCALAR, $IMPLT2 0 .. 1 (ORDERS ONLY) 13,
  32  VF1        RECORD FIELD, $IMPLT2 0 .. 1 (ORDERS ONLY)
  14  VF1        RECORD FIELD, $IMPLT2 0 .. 1 (ORDERS ONLY)
  32  VF2        RECORD FIELD, RECORD VF3 :, 32,
  16  VF2        RECORD FIELD, RECORD VF3 :, 24,
  32  VF3        RECORD FIELD, @REC1
  15  VF3        RECORD FIELD, @REC1
  10  V1         VARIABLE, BOOLEAN 0 .. 1 (ORDERS ONLY) 25, 25, 34
```

```
 11  V2          VARIABLE, @REC1 23, 24, 28,
 12  V3          VARIABLE, $IMPLT1 0 .. 1 (ORDERS ONLY)
 13  V4          VARIABLE, PACKED ARRAY (. CHAR 193 .. 233 (ORDERS
                  ONLY) .) OF PACKED ARRAY (. $IMPLT2 0 .. 1 (ORDE
                 RS ONLY) .) OF RECORD VF1 :, VF2 :, 24, 28, 32,
 35  X           VARIABLE, *** UNDEFINED ***

ERRNR SEMIC COL ERROR MESSAGE LISTING:      ***ERRONEOUS***

 101     2  44  IDENTIFIER '$LABEL1 ' DECLARED TWICE
 398     8  13  VARIANTS WILL BE TREATED AS RECORDS
 110     8  44  TAGFIELD TYPE MUST BE SCALAR OR SUBRANGE
 101     9  11  TWO RECORDFIELDS 'RF1 '
 104    10   5  IDENTIFIER 'REC2 ' UNDECLARED
 101    18  44  IDENTIFIER 'C2 ' DECLARED TWICE
 119    23   8  FORW. DCL.:MUST NOT REPEAT ARGUMENT LIST
 398    24  44  TAGFIELDVALUES IN PROC. 'NEW' IGNORED
 104    24   5  IDENTIFIER '$LABEL3 ' UNDECLARED
 135    24  12  TYPE OF OPERAND MUST BE BOOLEAN
 134    24  26  TYPE CONFLICT:'SCALAR ' VERSUS 'ARRAY '
 152    24  36  RECORD FIELD 'VF5 ' NOT FOUND
 154    25  22  ACTUAL PARAMETER MUST BE A VARIABLE
 134    26  23  TYPE CONFLICT:'SCALAR ' VERSUS 'SCALAR '
 104    28  44  IDENTIFIER 'OUTPUT ' UNDECLARED
 143    28  11  ILLEGAL TYPE OF LOOP CONTROL VARIABLE
 104    28  18  IDENTIFIER 'PP ' UNDECLARED
 104    30  44  IDENTIFIER '$LABEL4 ' UNDECLARED
 104    32  31  IDENTIFIER 'THREE ' UNDECLARED
 103    33  44  IDENTIFIER 'SR2 ' OF WRONG CLASS
 156    34  44  MULTIDEFINED CASE LABEL
 126    34  12  ACTUAL NUMBER OF ARGUMENTS UNEQUALS DCL.
 134    34  21  TYPE OF OPERAND(S) MUST BE BOOLEAN
  25    34  21  THEN EXPECTED,BUT = FOUND
 104    35   5  IDENTIFIER 'X ' UNDECLARED
 201    35   7  ERROR IN REAL CONSTANT: DIGIT EXPECTED
 398    35   7  REAL NUMBERS ARE NOT IMPLEMENTED
  26    35   8  FACTORLIST STARTS WITH IDENTIFIER
 167    36  44  UNSPECIFIED LABEL '4 '
 167    36  44  UNSPECIFIED LABEL '2 '
 167    36  44  UNSPECIFIED LABEL '1 '
 117    36  44  UNSATISF. FORWARD REFERENCE 'F '
```

2.10. Performance and Implementation Notes

The compiler is a single PASCAL program. It consists of 5400 lines of source code and its object module generated by the PASCAL 8000 (RPI Version) compiler occupies 160K bytes of storage, excluding a variable-sized run-time stack. The compiler is structured into 102 procedures and functions. It took the compiler 1.71 seconds to compile the program in section 1.16 on an IBM 3033 machine running under the Michigan Terminal System.

The compiler program uses three external files: INPUT for the program to be compiled, OUTPUT for compiler listings and messages, and SPUNCH for the lambda-calculus code produced. Only the first 100 characters of an input line are analyzed, and the maximum number of characters on code lines is currently set to 72. But these numbers can be changed easily. The routines generating a cross-reference were added for debugging purposes only and are coded rather inefficiently.

The following identifiers are pre-defined as in standard PASCAL: BOOLEAN, CHAR, CHR, FALSE, GET, INTEGER, ORD, PRED, PUT, REAL, SUCC, TRUE. INPUT or OUTPUT are files of INTEGER when specified as program parameters.

During the development of the compiler, the parser was actually generated automatically using a computer program. This program employs recursive PASCAL procedures, one for each non-terminal, in place of a pushdown stack [7]. Synthesized and inherited attributes become variable and value parameters respectively. A global switch is set if the parsing process attempts to recover from an erroneous input token. In this case, the body of a procedure is skipped if its corresponding symbol is supposed to be popped of the stack. It should be noted that this is just a method of coding an LL(1) parser and must not be confused with recursive descent methods [9].

The compiler itself is successfully processed by the parser.

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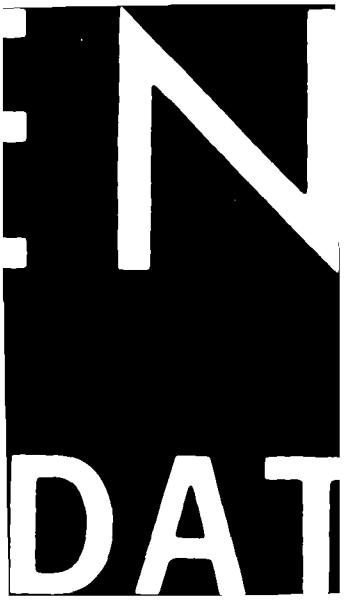
A Pascal compiler is described whose target language is the lambda-calculus instead of some machine code. Although the lambda-calculus code generated by this compiler can be executed by means of a lambda-expression reducer, the intended use of the translation is in proving programs correct. The compiler is written in Pascal itself, and contains an attributed LL(1) parser of the complete standard Pascal language. The error recovery is quite elaborate. The code generalization is done for a large subset of the language, covering: assignments, compound, conditional and repetitive statements, procedures including recursive calls and global side effects, multidimensional arrays.

This report contains a formal definition of the target language, a lambda-calculus model for the selected subset of Pascal, and a code-independent description of compilation algorithms including the complete LL(1) push-down automaton.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